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LARGE-SCALE CIRCULATION VARIABILITY AND IMPACTS ON NORTH INDIAN OCEAN TROPICAL CYCLONES

by

Adrian S. Christensen

March 2012

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ABSTRACT

Analysis of the relationships between different phases of El Niño-Southern Oscillation (ENSO), Indian Ocean Dipole (IOD), and Madden-Julian Oscillation (MJO) with tropical cyclone (TC) activity in the North Indian Ocean (NIO) is conducted. The relationships between ENSO and IOD are compared. Statistical analysis reveals a relationship exists. Each oscillation is examined to measure their statistical significance to TC activity in the NIO. The statistical examination was performed on the phases of each oscillation singularly and then all possible phase combinations of the three oscillations occurring concurrently. Analysis through combining concurrent occurrences of climatic oscillations indicates an increased statistical significance to TC activity in the NIO.

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LIST OF ACRONYMS AND ABBREVIATIONS

ACE	Accumulated Cyclone Energy
AS	Arabian Sea
BoB	Bay of Bengal
DMI	Dipole Mode Index
ENSO	El Niño-Southern Oscillations
EOF	Empirical Orthogonal Function
ESRL	Earth System Research Laboratory
IO	Indian Ocean
IOD	Indian Ocean Dipole
JTWC	Joint Typhoon Warning Center
MEI	Multi-variable ENSO Index
MJO	Madden-Julian Oscillation
OLR	Outgoing Longwave Radiation
SST	Sea-surface Temperature
TC	Tropical Cyclone

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I. INTRODUCTION

A. MOTIVATION AND OBJECTIVE

Few weather phenomena have the impact on society as tropical cyclones (TCs). These storms can cause loss of life and severe economical and environmental damage. Generally, TC impacts are due to devastating strong winds, massive flooding, and storm surge. In terms of military impact, operations are severely impacted, personnel evacuated, and facilities damaged.

In June 2007, a devastating tropical storm in the Arabian Sea named Gonu made landfall in Oman and then moved into Iran where it dissipated. It was the largest TC ever recorded to make landfall on the Arabian Peninsula and caused 4,500 deaths and $6.4 billion in damage. Every year, TCs in the North Indian Ocean (NIO) strike various coastline areas in East Africa and Southwest to South-central Asia from Somalia to Bangladesh. In response to various national factors, military activity by the U.S. Air Force and U.S. Navy has increased in the NIO. There is a need for better understanding of processes that impact TC activity over the NIO. Improved understanding will lead to more accurate forecasts that will protect lives, maximize effectiveness of military operations, and minimize damage to military and civilian property. One goal of this thesis is to provide the groundwork for future product development and research used for long-range forecasting of TC activity in the NIO.

Previous research has addressed the role(s) of various large-scale and slowly-varying air-ocean phenomena that define global circulations. These factors include the El Niño-Southern Oscillation (ENSO), Indian Ocean Dipole (IOD), and Madden-Julian Oscillation (MJO). While several studies (Rasmusson and Carpenter 1983; Saji, 1999; Madden and Julian 1971) have examined the individual impacts of these phenomena on TC activity over various ocean basins, few studies exist that examine how they interact. Furthermore, few studies have concentrated on the relationships among ENSO, IOD, and MJO with TC activity

over the NIO. If significant relationships among these climatic oscillations and TC activity in the NIO exist, long-range forecasts products can be developed based on common factors. A long-range TC forecast product for such a militarily important location in the world would prove very valuable. For this thesis, the following hypothesis will be investigated:

> The air-ocean characteristics associated with the ENSO, IOD, and MJO influence TC activity in the NIO and combinations of these oscillations jointly increase the statistically significant relationships with increased and decreased NIO TC activity.

B. BACKGROUND

1. Tropical Cyclones in the North Indian Ocean

Over the NIO, TCs develop in the Bay of Bengal (BoB) and Arabian Sea (AS) during two distinct seasons with peaks in activity in May–June and then October–December (Evan 2011). The high vertical wind-shear environment that results when the monsoon trough is displaced over the Indian subcontinent such that equatorial westerlies are below the upper-level tropical easterly jet, prevents TC occurrences during the prime monsoon season of the Northern Hemisphere summer. The peaks of NIO TC activity in the spring (pre-monsoon) and fall (post-monsoon) coincide with the placement of the monsoon trough to be between 5°–10°N latitude (Gray 1968).

The NIO is a relatively inactive TC basin when compared to other TC basins. The NIO accounts for only 7% of global tropical cyclone activity (Gray 1985). For this reason, few studies exist in regard to significant impacts of NIO TCs.

2. El Niño-Southern Oscillation

The ENSO refers to the oscillations of surface pressure and sea-surface temperature in the tropical Pacific Ocean (Rasmusson and Carpenter 1983). El Niño refers to the positive or warm phase of this oscillation in which high sea-

surface temperatures (SSTs) of the western tropical Pacific migrate eastward and convective precipitation increases over the central tropical Pacific (Figure 1). The eastward migration of high SSTs and increased convection occurs when the tropical easterlies weaken. La Niña is the negative or cold phase of ENSO in which high SSTs over the western tropical Pacific are confined to the maritime subcontinent region. Typically, the ENSO alternates between phases at an interannual temporal scale.

The ENSO is known to directly affect TC activity in the Pacific directly (Wu et al. 2004), and ENSO is also known to affect tropical cyclones around the globe through teleconnections (Moore et al. 2008). The variability in SSTs associated with ENSO alters global circulations that affect TC activity by changing vorticity in the lower levels and vertical wind shear throughout the troposphere (Diaz 2000). Over the NIO, recent research (Ng and Chan 2011) using accumulated cyclone energy (ACE) and total numbers of TCs indicated El Niño (La Niña) had a significant relationship to decreased (increased) TC activity. In this thesis, the relationship between ENSO and TC activity over the NIO will be examined.

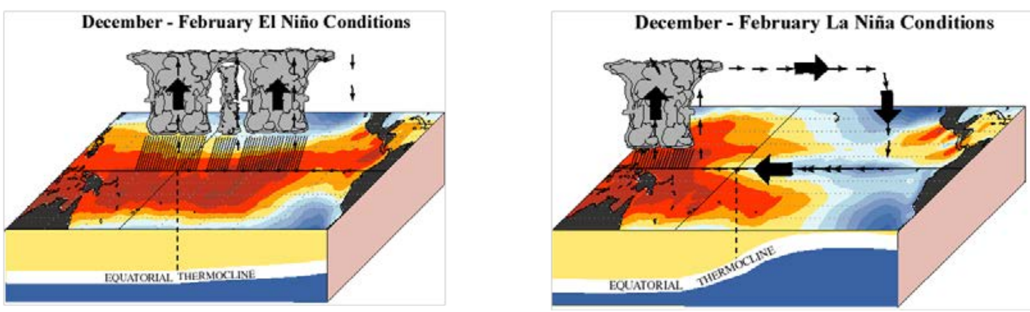

Figure 1. El Niño and La Niña stages of ENSO: El Niño conditions defined by weak equatorial easterly winds and high SSTs approach the east Pacific with increased convective precipitation in the central Pacific. La Niña is defined by strong equatorial easterly winds and high SSTs that are confined to the Maritime Continent with increased convective precipitation over Indonesia (From NOAA: http://www.cpc.ncep.noaa.gov/products/analysis_monitoring/ensocycle/enso_schem.shtml)

3. Indian Ocean Dipole

A climatic oscillation similar to ENSO also occurs in the Indian Ocean (IO). The Indian Ocean Dipole (IOD) is an oscillation between the SST of the western IO off the coast of Somalia and the SST over the eastern IO off the coast of Indonesia (Figure 2). When the western IO SSTs are higher than normal and the eastern IO SSTs are lower than normal, the IOD is in a positive phase. The negative phase is defined by the opposite SST anomaly pattern. Saji et al. (1999) defined this phenomenon and formation. Low SSTs tend to appear off the coast of Java in the late spring. By late summer, the low SST and easterly low level-wind surface anomalies intensify while the western tropical IO warms (Figure 2). The temporal scale over which the IOD varies is smaller than for ENSO. It is common for the phases of the IOD to oscillate several times a year (Saji et al. 1999).

The characteristics associated with the IOD were recently examined by Saji et al. (1999) in comparison to the various phases of ENSO. Less is known about the global impacts associated with the IOD. However, there is some evidence that the IOD impacts climate in the local regions of Indonesia and East Africa (Behera et al. 2005, D'Arrigo and Wilson 2008).

Ng and Chan (2011) have indicated that the positive IOD (negative IOD) has a statistically significant relationship to decreased (increased) NIO TC activity. Their study established that IOD was negatively correlated at a significance level of 95% to accumulated cyclone energy (ACE), the number of tropical cyclones, and the number of intense tropical cyclones.

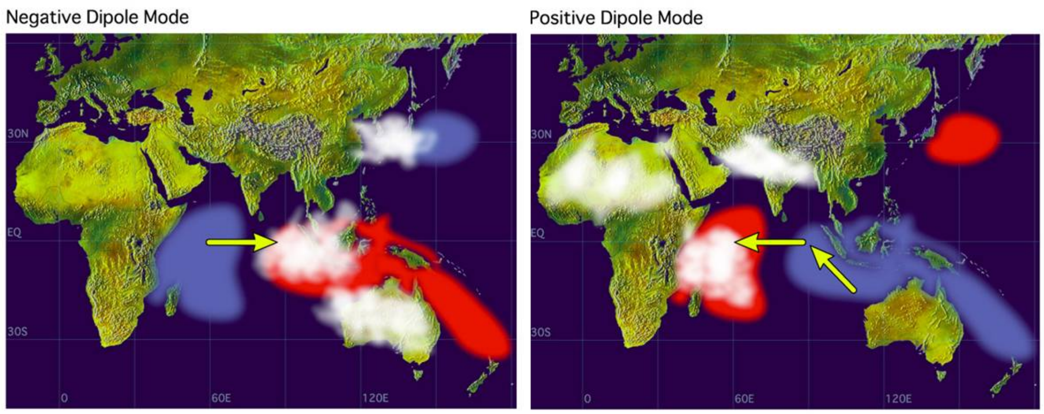

Figure 2. Schematic of positive IOD (left panel) and negative IOD (right panel). SST anomalies are shaded red (blue) for warm (cold). Cloud graphics indicate areas of increased convection. Arrows indicated anomalous low-level wind directions (From: http://www.jamstec.go.jp/frsgc/research/d1/iod/)

4. Madden-Julian Oscillation

The third type of climatic oscillation to be examined, which varies at the shortest temporal scale is the Madden-Julian Oscillation (MJO) (Madden and Julian 1971). The MJO is an intraseasonal oscillation of surface and upper-level wind anomalies over the tropics (40–50 days) (Madden and Julian 1971). Atmospheric features that define the MJO include anomalous low and upper-level winds, convective rainfall, and cloud cover. These anomalies propagate west to east around the globe and are strongest in intensity over the tropical Indian and Pacific Oceans (Madden and Julian 1994; Rui and Wang 1990). The positive anomaly of convective rainfall associated with the MJO propagates simultaneously with an area of a negative anomaly in tropical convection over a different part of the world. The mechanism responsible for the propagation of the MJO is generally thought to be defined by air-sea interaction differences between convective and non-convective regions. However, specific initiation factors are unknown at this time.

An MJO index has been developed by Wheeler and Hendon (2004), that can be used in the prediction and monitoring of the MJO. The index defines the

MJO by strength and location around the globe based on outgoing longwave radiation (OLR) and wind anomalies at 850 hPa (Wheeler and Hendon 2004). The MJO index is defined by a two-dimensional phase space based on empirical orthogonal functions (EOFs) of the wind and OLR anomalies. In this phase space (Figure 3), the MJO is defined to be in one of eight regions that span the globe. The MJO index is scaled such that an amplitude greater than 1.0 indicates the presence of the MJO.

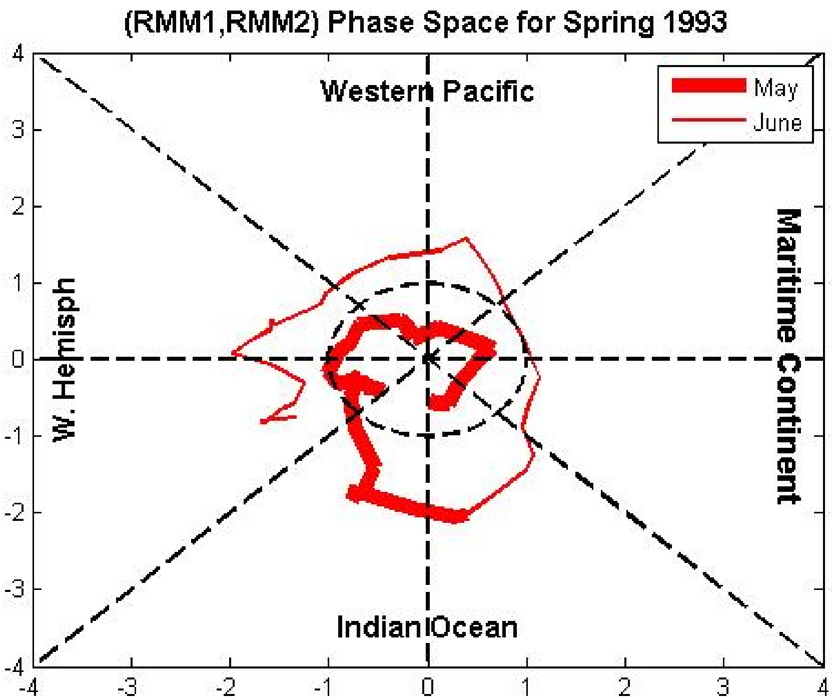

Figure 3. Phase space defined by the MJO index (2004)

Past studies have defined robust relationships between the MJO and tropical cyclones in the Pacific, Atlantic, and Indian Oceans (Higgins and Shi 2001). Klotzbach (2010) specifically indicated a relationship between Atlantic TCs and an MJO over the Western Hemisphere, which corresponds to phases 1 and 2 in the MJO index phase space. The MJO provides a large-scale environment that is favorable for TC development. Low-level westerly surface anomalies behind the area of convection contribute to increased cyclonic vorticity

over equatorial latitudes (Figure 4). Upper-level easterly anomalies contribute to upper-level divergence that is favorable for maintenance of deep convection that may contribute to TC development (Figure 4).

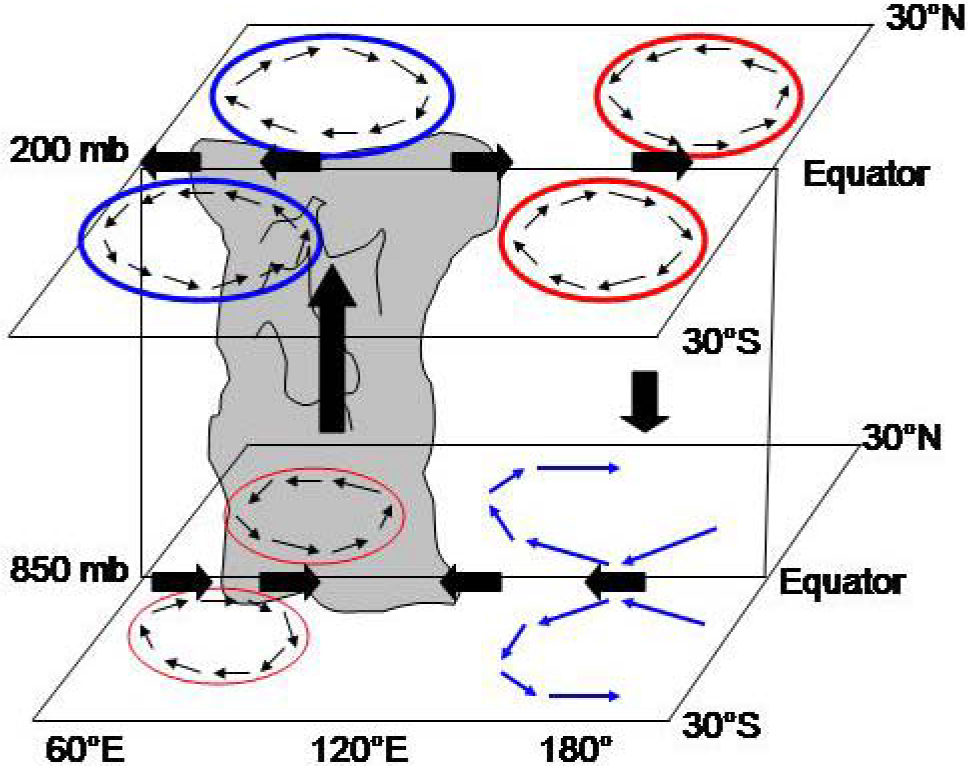

Figure 4. Schematic of an idealized MJO cycle from Higgins and Shi (2001). The shaded area defines a region of deep convection. Circles and the arrows define individual lower-and upper-level circulations with the primary MJO circulations defined by the bold arrows.

5. Past Studies of ENSO/IOD/MJO Interaction

Several past studies have examined the interaction between the ENSO and IOD, as well as the relationship between MJO with ENSO and IOD. However, some uncertainty exists in the relationship between the IOD and ENSO. Rao et al. (2002) and Yamagata et al. (2004) indicated that only 30% of IOD events develop in conjunction with ENSO. Other studies (Baquero-Bernal et al. 2002, Dommenget and Latif 2002, Hastenrath 2002) have concluded that the IOD is an extension of ENSO into the Indian Ocean.

Studies from Kessler and Kleeman (2000) and Zhang and Gottschalck (2002) indicated a possible relationship between seasonal MJO activity in the west Pacific and SST anomalies associated with the onset of ENSO phases in the east Pacific. Rao and Yagamata (2004), Seiki and Takayabu (2007a), and Sooraj et al. (2009) have indicated that MJO activity is influenced by the IOD. Ashok and Guan (2004) showed the combined influences of ENSO and IOD impact the evolution of the Indian Summer Monsoon.

In summary, previous studies indicate that linkages exist among IOD, ENSO, and MJO. The combined influences of the ENSO and IOD impact the Indian Summer Monsoon, which in turn affects NIO TC activity. The preceding studies lead to a hypothesis that combinations of ENSO, IOD and MJO, will have an even stronger relationship to TC activity in the NIO than any one oscillation singularly.

In this thesis, these large-scale, atmospheric-ocean systems will be examined with respect to their impacts on TC activity in the NIO. A rigorous statistical analysis is applied to establish significant relationships among the large-scale system and TC activity. The most significant relationships will then be examined to define low-level features that statistically relate to the character of the large-scale environment and TC activity.

II. METHODOLOGY

A. DATA

This thesis examines tropical cyclone data from 1979–2010 that are contained in the Joint Typhoon Warning Center (JTWC) Annual Tropical Cyclone reports. Post-1978 tropical cyclones were chosen because that is when the annual tropical cyclone counts are most consistent, and satellite data were routinely available (Evan and Camargo 2011).

The multivariable ENSO Index (MEI) was used to determine the ENSO phases. The MEI was obtained from the Earth System Research Laboratory (ESRL), (http://www.esrl.noaa.gov/psd/enso/mei/mei.html). The MEI combines six meteorological and oceanic variables into one bi-monthly index to characterize states of ENSO in the tropical Pacific (Wolter and Timlin 1993). Monthly terciles were computed using MEI values since 1948. The upper tercile defines El Niño conditions, the lower tercile defines La Niña conditions, and the middle tercile defines neutral conditions.

To define phases of the IOD, SST data were needed to compute the Dipole Mode Index (DMI). The SSTs were obtained from the NCEP/NCAR reanalysis (Kalnay et al. 1996). The DMI is based upon the SST differential between the western equatorial Indian Ocean (50° E-70°E and 10° S-10°N) and the eastern equatorial Indian Ocean (90° E-110°E and 10° S-0°S) (Saji et al. 1999). A warm anomaly in the western IO and cold anomaly in the eastern IOD defines a positive DMI. A cold anomaly in the western IO with a warm anomaly in the eastern IO is a negative DMI. Monthly DMI values since 1948 were computed and divided into terciles in the same manner as the MEI index.

The MJO index data were obtained from the Australian Bureau of Meteorology website (http://www.bom.gov.au/climate/mjo/). The MJO index is derived from outgoing longwave radiation (OLR), zonal wind, and merdional wind. As discussed in Chapter I, Wheeler and Hendon (2004) developed this

index to classify the MJO by strength and location. Their MJO index describes the location and intensity of the MJO over eight phases across the global tropics.

B. STATISTICAL METHODS OF ANALYSIS

The lifespan of a TC in this study was defined by the first and last dates in each storm record of the JTWC annual storm reports. In addition, the JTWC classifies all NIO TCs as either AS or BoB.

The NIO TC activity is usually restricted to two primary seasons that are defined as May–June and September–December. These months were chosen for examination. However, the MEI and DMI tercile computations were performed as discussed in the previous section and were based on all months.

For each month in the dataset, the daily MJO index was binned into nine categories based on the eight phases from the Wheeler-Hendon diagram for strong MJO events as well as a "weak" category for periods when the MJO amplitude was less than one. The number of days in each MJO category were defined every month for the entire dataset. These processes were repeated, but only counting the specific days a TC was present in the NIO, i.e., TC days.

As defined in Chapter I, a primary objective is to examine the effects of ENSO, IOD, and the MJO on TC activity in the NIO. One of the challenges is to account for the varying temporal scales. The indices used for measuring ENSO and IOD are measured on monthly time intervals while the MJO is measured on daily time intervals. A TC will be labeled according to the ENSO, IOD, and MJO conditions present for Day 1 of the TC lifespan so as to best capture TC formation.

Statistical analysis throughout this research was based on the method used by Hall et al. (2000). The null hypothesis is that cyclones are uniformly distributed among states of each environmental factor (ENSO, IOD, or MJO). This leads to use of the binomial distribution as the basis for the test statistic, Z, which is defined as,

$$Z = \frac{P - Po}{Sp}.$$

The observed proportion of TC days or months is defined by P and the total proportion of days or months is defined by Po. The normalization factor, Sp, is defined as $Sp = \sqrt{\left\{\frac{Po(1 - Po)}{N}\right\}}$ where N is the total number of days in each category. The variable C defines the subset of N cases that correspond to the event of interest (i.e. TC days) (Table 1).

The test statistic assumes a Gaussian distribution with zero mean and unit standard deviation. All statistical tests throughout this research were examined using a two-tailed test at 95%, which is defined as statistically significant. To reach a statistical significance of 95%, the valid critical value is Z = ±1.96.

In the example in Table 1, the TC activity during each ENSO category is examined. For example, 54 El Niño months had a TC while 69 total El Niño months occurred, which leads to a P value of 0.785. In addition, of the 192 total El Niño months, 161 of these months contained a TC. Therefore, the value of Po is 0.839. The computation of Sp leads to a Z value of -1.26. Since this value is not more negative than the critical value of -1.96, no significant relationship exists between El Niño and NIO TC activity. However, the Z value for La Niña (neutral ENSO) was 3.75 (-2.338), which indicates that there is a positive (negative) impact on TC activity during La Niña (neutral ENSO) conditions.

		Total Storms MEI		
ENSO/DMI Category	El Niño	Neutral	La Niña	Total
# TCs (C)	54	46	61	161
Total Months (N)	69	63	60	192
P	0.783	0.730	1.017	0.839
Po	0.839	0.839	0.839	
1-Po	0.161	0.161	0.161	
Po(1-Po)	0.135	0.135	0.135	
(Po(1-Po)/N	0.002	0.002	0.002	**Normal Distribution**
Sp	0.044	0.046	0.048	**Critical Value at 95%**
Z	-1.260	-2.338	3.750	**Z= -1.96 and +1.96**

Table 1. Example of statistical analysis method performed in this research. Categories where numbers were significantly above (below) average at the 95% level are indicated by red (blue).

C. COMPOSITION OF ZONAL WIND AND CONVECTIVE PRECIPITATION

Based on the results of the statistical analysis, significant impacts on TC activity due to individual or combinations of circulation features are examined by compositing 850 hPa zonal winds and convective precipitation. The composites are defined by combining all days associated with the statistically significant circulation feature. Differences between composite conditions associated with positive and negative impacts on TC activity are defined. Statistically significant differences are identified by applying the two-tailed t-test to examine whether the differences are different than zero.

The composites are constructed from the NCEP/Department of Energy Reanalysis II. The Reanalysis II product improves on the Reanalysis I (Kalnay et al. 1996) by correcting known errors and improving the parameterization of physical processes.

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III. ANALYSIS AND RESULTS

A. ENSO/IOD RELATIONSHIP

1. Total TC Months

All months in the Fall and Spring TC seasons were compared to see if certain phases of ENSO favored certain phases of IOD. The calculation investigates whether the slowly -varying, larger-scale ENSO phenomenon has an impact on the faster-varying, smaller-scale IOD. The specific question is whether during each of the three ENSO periods (El Niño, neutral, and La Niña) the numbers of months in each of the three terciles of IOD (positive, neutral, and negative) depart significantly from a uniform distribution.

Positive IOD events are indeed favored in the Pacific during El Niño periods (Figure 5) (Table 2) since over half of all positive IOD months occurred during El Niño months (Figure 5) (Table 2). As one might expect, the lower temperatures that exist in the eastern IO during the positive IOD phase occur most often with lower SSTs over the western Pacific. The opposite is true for occurrences negative IOD during El Niño periods as a statistically significant inverse relationship exists. No statistically significant relationship was found for the neutral IOD phase months and El Niño periods (Figure 5) (Table 2).

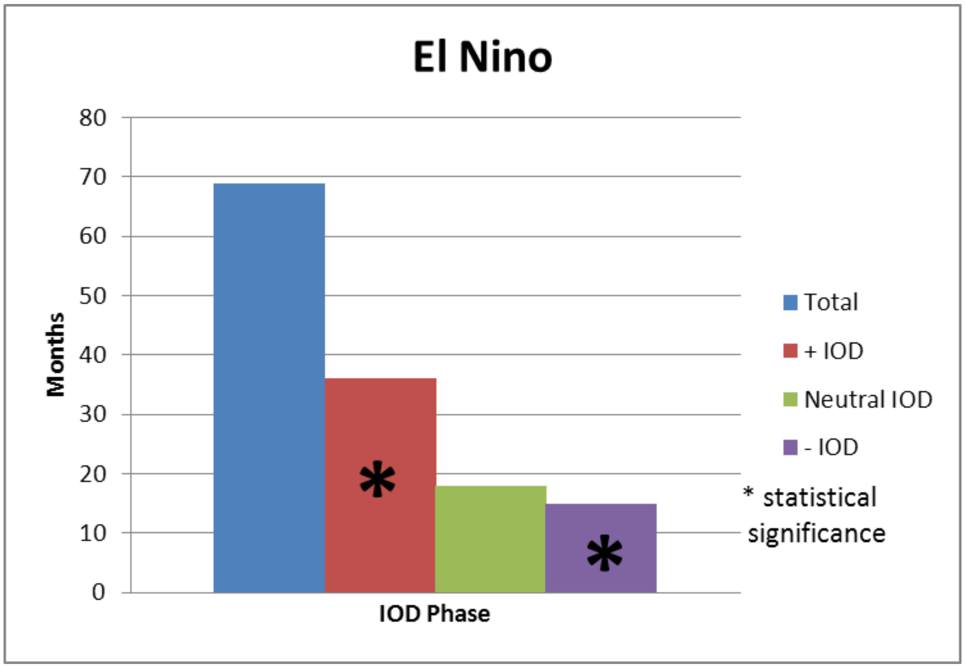

Figure 5. Histogram of monthly IOD distributions during periods of El Niño

During neutral ENSO periods, no statistical significant relationships exist with any phase of the IOD (Figure 6) (Table 2).

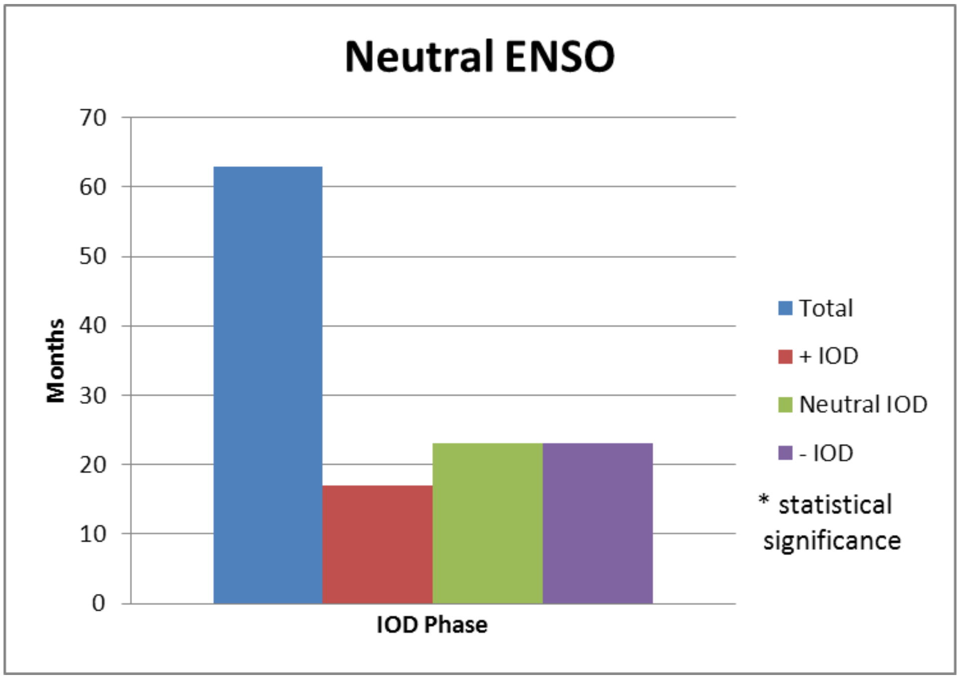

Figure 6. Histogram of months with IOD values as in Figure 5, except during periods of neutral ENSO.

The relationships during La Niña periods with the different phases of the IOD were found to be opposite from the relationships during El Niño periods. A statistically significant relationship was found for the negative IOD, while a significant inverse relationship was found with the positive IOD (Figure 7) (Table 2). No statistical relationship was found for the neutral IOD, just as was the case for periods of El Niño (Figure 7) (Table 2).

The statistically significant relationships found in the study are consistent with previous studies examining ENSO and IOD. Hastenrath (2002) suggested that the ENSO and IOD phenomena were linked such that the IOD defined an extension of the ENSO into the NIO.

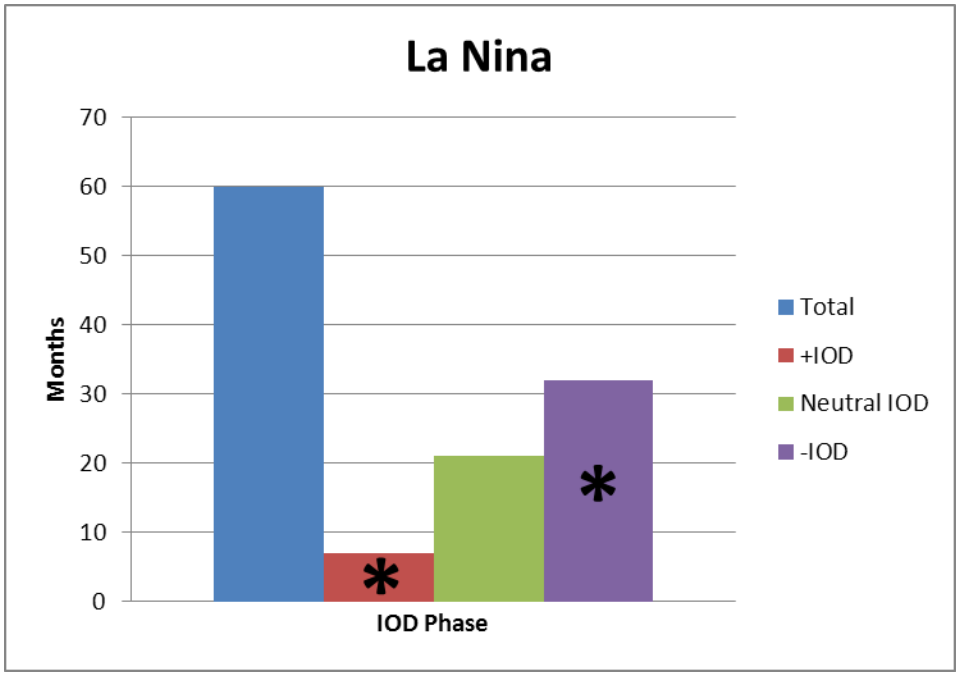

Figure 7. Histogram of months with IOD values as in Figure 5, except during La Niña periods.

ENSO/IOD Relationship				
		# Months	Total IOD Months	Z-Value
+IOD	El Niño	36	69	3.75
+IOD	Neutral ENSO	17	63	-0.73
+IOD	La Niña	7	60	-3.27
Neutral IOD	El Niño	18	69	-1.10
Neutral IOD	Neutral ENSO	23	63	0.72
Neutral IOD	La Niña	21	60	0.45
-IOD	El Niño	15	69	-2.54
-IOD	Neutral ENSO	23	63	0.01
-IOD	La Niña	32	60	2.72

Table 2. Statistical analysis of significant relationships among ENSO and IOD phases. Cells shaded red indicate a 95% significance of a positive relationship. Cells shaded blue indicate 95% significance to a negative relationship.

2. Separate Spring and Fall Months

The ENSO and IOD relationships were also examined after separating the months into Fall and Spring NIO TC seasons. For the Spring periods, all statistical significant relationships between IOD and ENSO that were found in the previous section fell below the critical value of 95% (Figures 8, 9, 10) (Table 3).

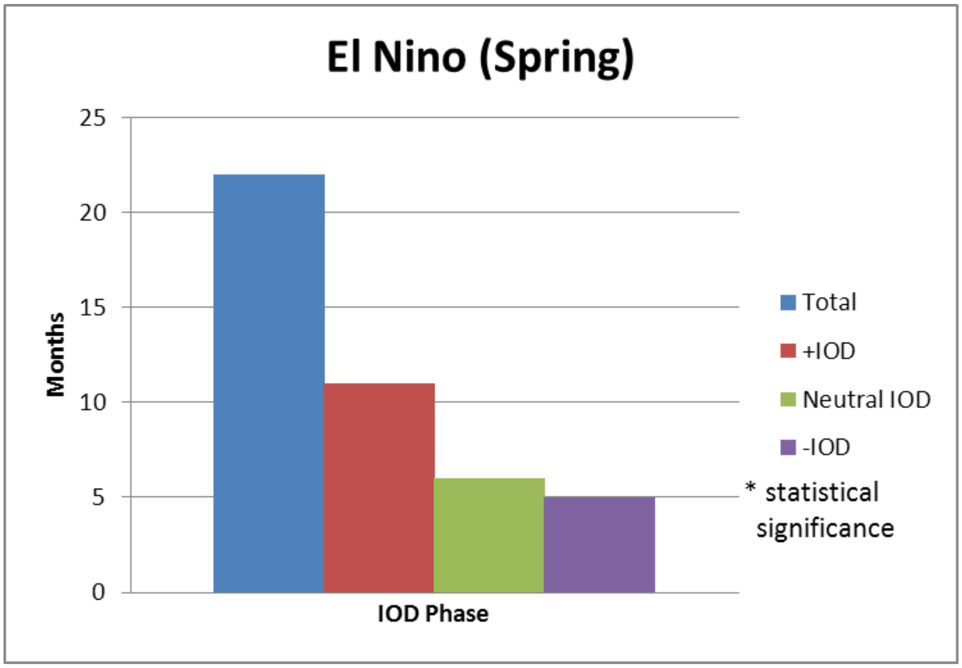

Figure 8. Histogram of months with IOD values as in Figure 5, except during El Niño periods and only during the NIO Spring TC months.

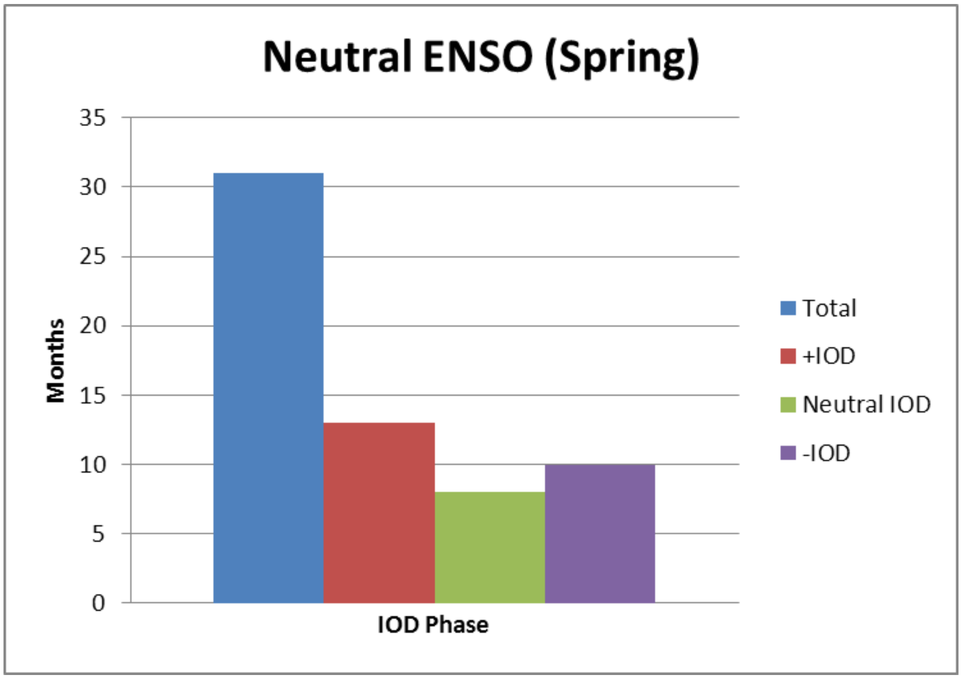

Figure 9. Histogram of months with IOD values as in Figure 5, except during neutral ENSO periods and only during the NIO Spring TC months.

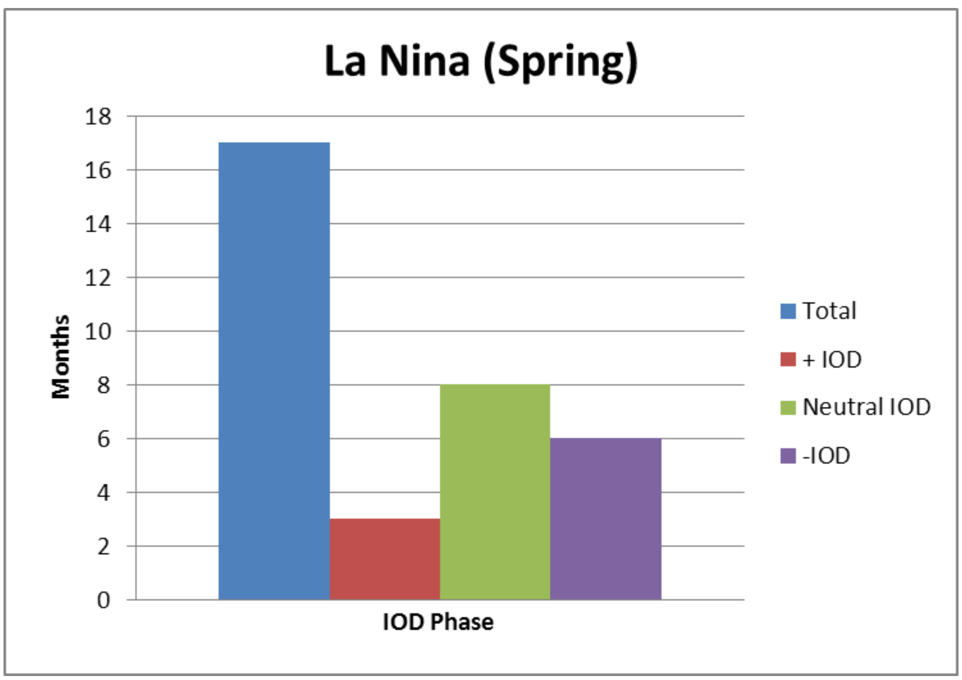

Figure 10. Histogram of months with IOD values as in Figure 5, except during La Niña periods and only during the NIO Spring TC months.

Spring ENSO/IOD Relationship (May-June)				
		# Months	Total DMI Months	Z-Value
+IOD	El Niño	11	22	0.90
+IOD	Neutral ENSO	13	31	0.15
+IOD	La Niña	2	11	-1.52
Neutral IOD	El Niño	5	22	-1.01
Neutral IOD	Neutral ENSO	10	31	-0.07
Neutral IOD	La Niña	6	11	1.54
-IOD	El Niño	5	22	0.08
-IOD	Neutral ENSO	10	31	-0.10
-IOD	La Niña	6	11	0.05

Table 3. Statistical analysis of the TC relationships among ENSO and IOD phases during the Spring. Cells shaded red indicate a 95% significance to direct to a relationship. Cells shaded blue indicate 95% significance to a negative relationship.

The same statistically significant relationships identified for the sample of all months were also found to be significant for the Fall NIO TC months only. That is, significant relationships are found for positive IOD months during and El Niño periods, as well as negative IOD months during La Niña (Figures 11 and 13) (Table 4). Also, an inverse relationship exists for the negative IOD values during El Niño periods and similarly with positive IOD during periods of La Niña (Figure 11 and 13) (Table 4). Again, no statistically significant relationships were found for the neutral IOD values during any ENSO period (Figure 12) (Table 4). The occurrence of statistically significant relationships of the IOD values and ENSO in the Fall may be related to the strengthening ENSO cycles that typically occur in the Fall (Rasmusson and Carpenter 1982).

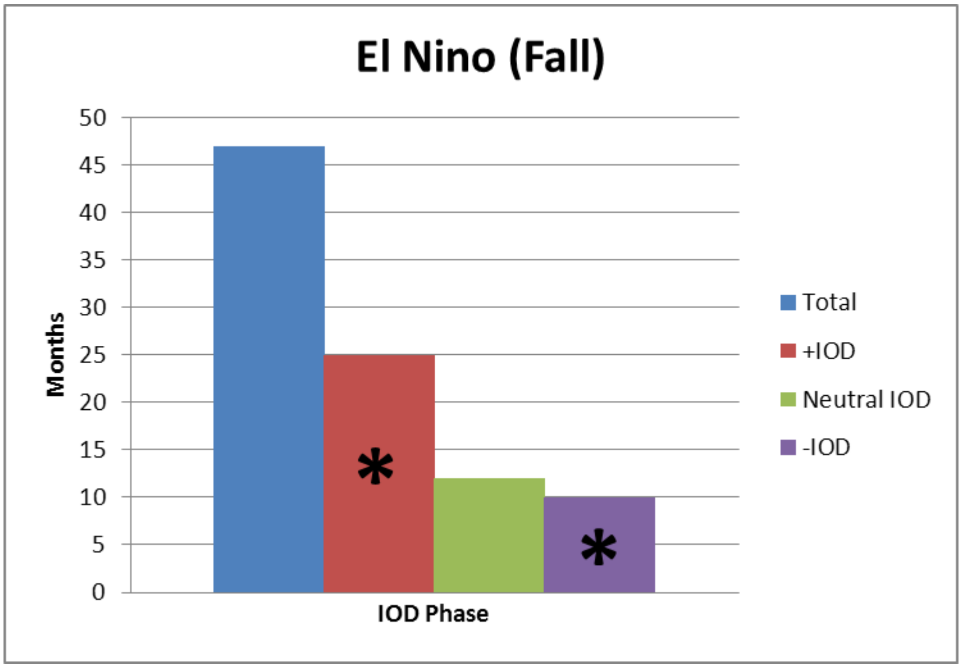

Figure 11. Histogram of months with IOD values as in Figure 5, except during El Niño periods for NIO Fall TC months.

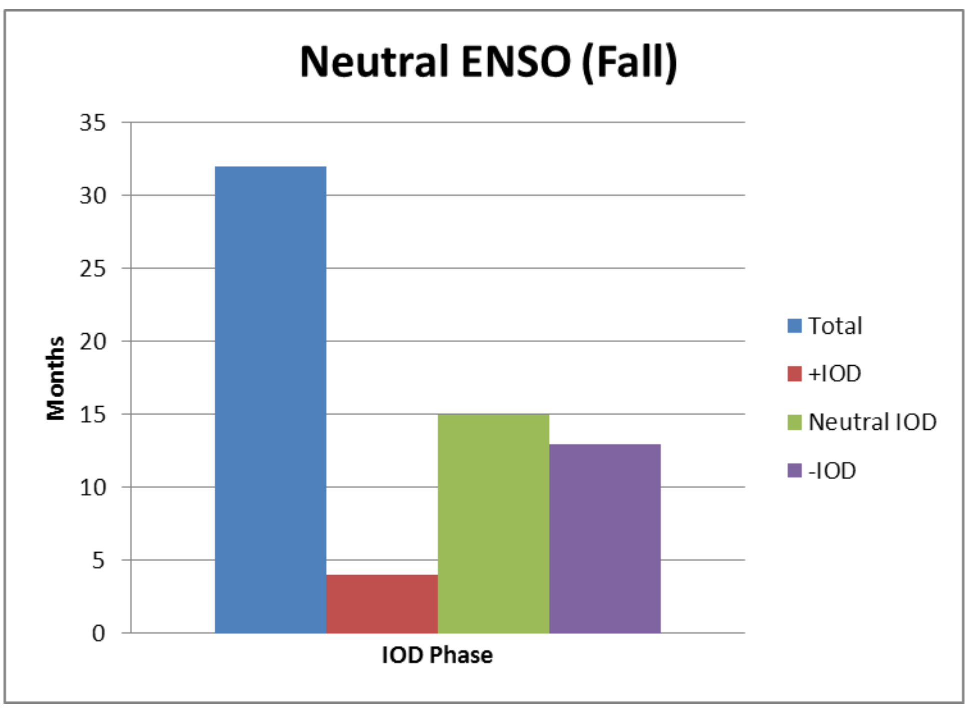

Figure 12. Histogram of months with IOD values as in Figure 5, except during neutral ENSO periods for NIO Fall TC months.

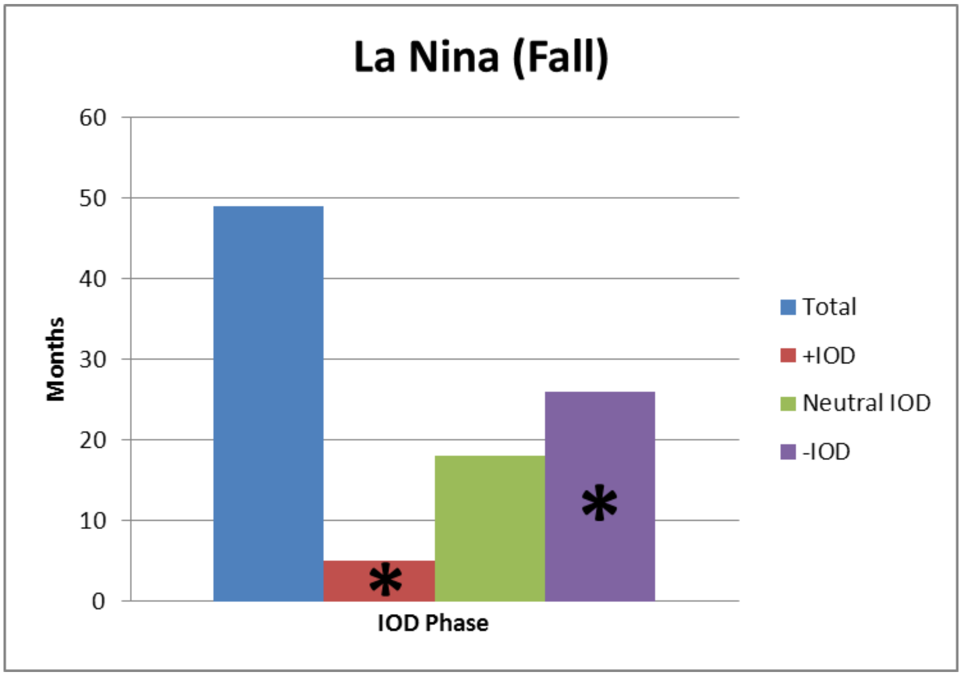

Figure 13. Histogram of months with IOD values as in Figure 5, except during neutral ENSO periods for NIO Fall TC months.

Fall ENSO/IOD Relationship (Sep-Dec)				
		# Months	Total DMI Months	Z-Value
+IOD	El Niño	25	47	4.13
+IOD	Neutral ENSO	4	32	-1.80
+IOD	La Niña	5	49	-2.59
Neutral IOD	El Niño	10	47	-1.38
Neutral IOD	Neutral ENSO	13	32	1.39
Neutral IOD	La Niña	26	49	0.23
-IOD	El Niño	12	47	-2.40
-IOD	Neutral ENSO	15	32	0.27
-IOD	La Niña	18	49	2.13

Table 4. Statistical analysis of significant relationships among ENSO and IOD phases during the Fall. Cells shaded red indicate a 95% significance to a positive relationship. Cells shaded blue indicate 95% significance to a negative relationship.

B. ENSO/IOD RELATIONSHIPS WITH NIO TC ACTIVITY

1. ENSO Phase-Only Relationships

The relationships among the three phases of ENSO and IOD with TC activity were next analyzed. For the sample of all NIO TCs, a significant positive relationship exists between La Niña and TC activity in the NIO with 61 TCs occurring in 60 La Niña months (Table 5, row 3). In contrast, neutral ENSO months were found to correspond to reduced TC activity (Table 5, row 2). Overall, there is no statistical significance between El Niño months and TC activity in the NIO (Table 5, row 1).

Separate samples of TCs that occurred in the BoB and AS were also categorized by ENSO phase and the same analysis was performed. For the sample of AS TCs, a significant relationship does not exist between any ENSO phase and AS TCs (Table 6, rows 1–3). A significant relationship exists between La Niña and increased TC activity over the BoB (Table 7, rows 1–3). The higher SSTs in the region of the Maritime Continent associated with La Niña also significantly impacts the number of TCs in the BoB, but not in the AS.

2. IOD Phase-Only Relationships

Recall from Table 4 that a direct relationship was discovered between La Niña and positive IOD, as well as El Niño and negative IOD. Noting then from Tables 5–7 that La Niña (El Niño) periods increased (decreased) TC activity in the NIO, it is hypothesized that a negative IOD would be related to statistically significant increased TC activity in the NIO, while a positive IOD would be related to decreased TC activity. These relationships are indeed confirmed in rows 6 and 4, respectively, in Table 5. However, no statistically significant relationship is found between the neutral IOD and TC activity (Table 5, row 5).

As was done with ENSO analysis, the relationship between TC activity in the NIO and IOD was examined separately for BoB (Table 7) and AS (Table 6) TCs.

Unlike what was found in the ENSO analysis, no statistical significance favoring a particular phase of IOD was found for either AS or BoB storms (rows 4–6 in Tables 6 and 7) when analyzed separately.

3. ENSO + IOD Combined Relationships

The relationships among the phases of ENSO and IOD with TC activity have been examined individually. The next step to fully understand the relationship between these two large-scale circulation and TC activity is to identify their combined impact on TC activity in the NIO.

Whereas no statistically relevant relationship to TC activity in the NIO was found during El Niño conditions (Table 5), when El Niño conditions occur in conjunction with a positive IOD a negative impact on TC activity is found (Table 5, row 7). In addition, TC activity in the NIO is also suppressed during El Niño periods and a neutral IOD (Table 5, row 8). This is interesting because individually El Niño and neutral IOD have no statistically significant relationship with TC activity in the NIO. Finally, El Niño in conjunction with a negative IOD has a significant increase in TC activity (Table 5, row 9), which indicates that the tendency of negative IOD to have increased TC activity has a larger impact than the tendency of El Niño periods to have no significant positive or negative impact on TC activity.

Recall again the evidence in Table 4 of a direct relationship between La Niña conditions in the Pacific Ocean and negative IOD in the Indian Ocean. From Table 5, significantly more TC activity occurs in the NIO during La Niña conditions and also during a negative IOD. These factors produced the expected result that significantly more TC activity occurs when La Niña and negative IOD occur together (Table 5, row 15).

By contrast, a positive IOD is related to significantly less TC activity in the NIO. When positive IOD was examined in conjunction with La Niña conditions, the tendency for La Niña conditions to have more TC activity was counteracted by the suppression tendency from positive IOD.

As a result, no statistical significance with TC activity could be identified (Table 5, row 13). No statistical significance was also found when La Niña occurred in conjunction with neutral DMI (Table 5, row 14).

The final ENSO/IOD relationship to be examined was the relationships between different phases of IOD in conjunction with a neutral ENSO. Recall from Table 5 (row 2) that the neutral ENSO is related to suppressed TC activity. Whereas positive IOD is also associated with suppressed TC activity, significantly reduced TC activity also occurred (Table 5, row 10) when positive IOD and neutral ENSO conditions occur together.

When a negative IOD that is related to increased TC activity over the NIO (Table 5, row 6) occurs in conjunction with the neutral ENSO phase that is related to suppressed activity, the two tendencies counteract one another. Therefore, no statistically significant relationship to TC activity is found (Table 5, row 12).

Finally, neutral IOD conditions, which have no statistical relationship to TC activity, tend to offset the negative TC relationship of neutral ENSO conditions enough that a significant impact on TC activity in the NIO no longer exists at a 95% critical value (Table 5, row 11). However, if the test statistic is reduced to -1.86, it could be that a neutral IOD/neutral ENSO pairing might be related to decreased TC activity.

ENSO/IOD Relationship to TCs in NIO				
		# TCs	Total Months	Z-Value
El Niño only		54	69	-1.26
Neutral ENSO only		46	63	-2.34
La Niña only		61	60	3.75
+DMI only		41	60	-3.27
Neutral DMI only		50	62	-0.69
-DMI only		70	70	3.67
El Niño	+IOD	24	36	-2.80
El Niño	Neutral IOD	12	18	-1.98
El Niño	-IOD	18	15	3.80
Neutral ENSO	+IOD	11	17	-2.15
Neutral ENSO	Neutral IOD	19	23	-0.16
Neutral ENSO	-IOD	16	23	-1.86
La Niña	+IOD	6	7	0.13
La Niña	Neutral IOD	19	21	0.82
La Niña	-IOD	36	32	4.40

Table 5. Statistical significance between ENSO phases (first three rows), IOD phases (fourth through sixth rows) or ENSO phases in conjunction with IOD phases (seventh through 15th rows) and TC activity in the NIO. Cells shaded red indicate a 95% significance to increased TC activity. Cells shaded blue indicate 95% significance to decreased activity

When the same statistical analysis is applied to only the TCs in the AS (Table 6), none of these statistically significant results for the entire NIO remain true. This result is likely related to the small numbers (only one to nine) of TCs in the samples when combinations of ENSO and IOD phases are considered. In the case of TCs in the BoB (Table 7), only two combinations of ENSO and IOD phases result in statistically significant relationships. Just as in Table 5, the most significant relationship is the increased number of TCs for the combinations of La Niña and negative IOD conditions (Table 7, row 15).

ENSO/IOD Relationship to TCs in AS				
		# TCs	Total Months	Z-Value
El Niño only		19	69	0.49
Neutral ENSO only		16	63	0.07
La Niña only		13	60	-0.60
+DMI only		11	60	-1.19
Neutral DMI only		15	62	-0.15
-DMI only		22	70	1.24
El Niño	+IOD	8	36	-0.38
El Niño	+IOD	5	18	0.27
El Niño	+IOD	6	15	1.34
Neutral ENSO	Neutral IOD	2	17	-1.26
Neutral ENSO	Neutral IOD	7	23	0.60
Neutral ENSO	Neutral IOD	7	23	0.60
La Niña	-IOD	1	7	-0.65
La Niña	-IOD	3	21	-1.13
La Niña	-IOD	9	32	0.41

Table 6. Statistical significance among ENSO phases, IOD phases, or ENSO phases in conjunction with IOD and TC activity as in Table 5, except for only the sample of TCs in the AS. Cells shaded red indicate a 95% significance to increased TC activity. Cells shaded blue indicate 95% significance to decreased activity.

ENSO/IOD Relationship to TCs in BoB				
		# TCs	Total Months	Z-Value
El Niño only		**35**	**69**	**-1.37**
Neutral ENSO only		**30**	**63**	**-1.81**
La Niña only		**48**	**60**	**3.33**
+DMI only		**30**	**60**	**-1.39**
Neutral DMI only		**35**	**62**	**-0.38**
-DMI only		**48**	**70**	**1.65**
El Niño	**+IOD**	**16**	**36**	**-1.76**
El Niño	**+IOD**	**7**	**18**	**-1.72**
El Niño	**+IOD**	**12**	**15**	**1.66**
Neutral ENSO	**Neutral IOD**	**9**	**17**	**-0.50**
Neutral ENSO	**Neutral IOD**	**12**	**23**	**-0.65**
Neutral ENSO	**Neutral IOD**	**9**	**23**	**-1.92**
La Niña	**-IOD**	**5**	**7**	**0.68**
La Niña	**-IOD**	**16**	**21**	**1.61**
La Niña	**-IOD**	**27**	**32**	**2.93**

Table 7. Statistical significance among ENSO phases, IOD phases, or ENSO phases in conjunction with IOD and TC activity as in Table 5, except for only the sample of TCs in the BoB. Cells shaded red indicate a 95% significance to increased TC activity. Cells shaded blue indicate 95% significance to decreased activity.

C. MJO PHASE ANALYSIS

As explained in the methodology section, eight phases of the MJO are based on locations around the globe. With the addition of a weak MJO, which is defined as an index amplitude less than one, there are nine MJO categories. This study identifies relationships in certain MJO phases that relate to suppression or enhancement of TC activity in the NIO.

1. All TCs/MJO Relationships

Interactions of global circulations on two time scales have been examined in the previous section with respect to their impact on TC activity.

The ENSO is associated with an interannual timescale and IOD is associated with an intraseasonal-to-interannual timescale. In this section, the third timescale being investigated is how the MJO, at a timescale of a month or less, affects TC activity.

Each day since 1979 was first categorized by the MJO phase. The distribution of TC activity among the MJO phases was examined within the normal distribution method described in the methodology section against all NIO TC days. A strong relationship exists between MJO phases 3, 4, and 5 and enhanced TC activity in the NIO (Table 8). The most significant relationship exists with phase 4 (Table 8). For the rest of this study, an MJO in one of these three phases will be classified as "convective". Additionally, a significant relationship was found between decreased TC activity in the NIO when the MJO was in phases 7, 8, and 1 (Table 8). For the remainder of this study, an MJO in one of the three aforementioned MJO phases will be known as "non-convective". Finally, an MJO with amplitude of less than one will be designated as "weak" for the remainder of this study.

MJO Phase/TC Relationship				
MJO Phase		**# TC Days**	**Total Days**	**Z-Value**
1	**Total Days**	**40**	**445**	**-3.20**
2	**Total Days**	**55**	**488**	**-1.91**
3	**Total Days**	**95**	**409**	**5.16**
4	**Total Days**	**138**	**452**	**9.86**
5	**Total Days**	**114**	**511**	**5.17**
6	**Total Days**	**51**	**454**	**-1.87**
7	**Total Days**	**20**	**403**	**-5.35**
8	**Total Days**	**19**	**434**	**-5.90**
9 (Weak)	**Total Days**	**305**	**2258**	**-1.07**

Table 8. Statistical analysis of significant relationships among phases of the MJO and TC activity in the NIO. Cells shaded red indicate a 95% significance to increased TC activity. Cells shaded blue indicate 95% significance to decreased activity.

2. El Niño/MJO Relationships

Specific MJO phases were analyzed to determine the impact TC activity for only El Niño periods. For the El Niño periods, phases 3, 4, and 5 are the only MJO phases that have a significant relationship to increased TC activity (Table 9). For these El Niño periods, the statistical significance of phase 4 increased even more (10.47) compared to the test statistic for all TCs (9.86). By contrast, the statistical significance for phases 3 and 5 both decreased but remained significant (Tables 8 and 9).

During these El Niño periods, phases 7, 8, and 1 have a statistically significant relationship to decreased TC activity in the NIO (Table 9), just as was found for the sample of all TCs. In addition, phase 6 and the weak MJOs were also found to have a significant relationship to decreased TC activity in the NIO. Phase 8 still has the strongest statistical negative relationship of all the phases (Table 9).

MJO Phase/ENSO/TC Relationship				
MJO Phase		**# TC Days**	**Total Days**	**Z-Value**
1	**El Niño**	**7**	**175**	**-3.30**
2	**El Niño**	**26**	**186**	**0.77**
3	**El Niño**	**44**	**219**	**3.60**
4	**El Niño**	**68**	**181**	**10.47**
5	**El Niño**	**29**	**151**	**2.66**
6	**El Niño**	**6**	**131**	**-2.65**
7	**El Niño**	**6**	**113**	**-2.22**
8	**El Niño**	**4**	**147**	**-3.50**
9 (Weak)	**El Niño**	**64**	**789**	**-3.47**

Table 9. Statistical analysis of significant relationships among phases of the MJO and TC activity in the NIO during periods of El Niño. Cells shaded red indicate a 95% significance to increased TC activity. Cells shaded blue indicate 95% significance to decreased activity.

3. Neutral ENSO/MJO Relationships

Analysis was performed for only the neutral ENSO periods as to how the specific MJO phases impact the TC activity. Compared with results from all TCs,

phases 3 and 4 are the only MJO phases found to be related to enhance TC activity at a 95% significant level (Table 10). Furthermore, phase 5 is no longer statistically significant, which may be interpreted as the region with the strongest relationship to TC activity in the NIO, is shifted westward during neutral ENSO periods.

During these periods of neutral ENSO, the most negative relationship with TC activity in the NIO occurred during phase 7 (Table 10). Phases 8 and 1 were no longer found to be statistically significant in relation to suppressed TC activity over the NIO (Table 10).

MJO Phase/ENSO/TC Relationship				
1	Neutral	22	155	0.77
2	Neutral	20	183	-0.52
3	Neutral	31	117	4.74
4	Neutral	29	123	3.87
5	Neutral	23	141	1.50
6	Neutral	11	134	-1.40
7	Neutral	10	165	-2.40
8	Neutral	15	168	-1.29
9 (Weak)	Neutral	70	711	-1.90

Table 10. Statistical analysis of significant relationships among phases of the MJO and TC activity in the NIO during periods of neutral ENSO. Cells shaded red indicate a 95% significance to increased TC activity. Cells shaded blue indicate 95% significance of decreased activity.

4. La Niña TC/MJO Relationships

Finally, analysis was performed on how specific MJO phases impact TC activity in the NIO for TCs during La Niña periods. During these periods, phase 5 has the strongest statistical significance and the relationship with phase 3 was no longer significant (Table 11). This result may be interpretation that the favorable region for TCs has been shifted eastward. In contrast to the neutral ENSO, a statistical significance is now found between weak MJOs and increased TC activity in the NIO (Table 11).

During these La Niña periods, phases 7, 8, and 1, have a statistically significant relationship with decreased TC activity in the NIO, and phase 8 has the strongest relationship (Table 11). These relationships are the same as identified with respect to all TCs (Table 8). However, MJOs over the western IO in phase 2 were found in La Niña periods to have a significant relationship to reduced TC activity in the NIO.

The analysis of the impact of the MJO on TC activity during specific ENSO periods found that the MJO reinforced the relationship with ENSO.

MJO Phase/ENSO/TC Relationship				
1	La Niña	11	115	-2.49
2	La Niña	9	119	-3.10
3	La Niña	19	73	1.63
4	La Niña	41	148	2.84
5	La Niña	62	219	3.69
6	La Niña	34	189	-0.22
7	La Niña	4	125	-4.43
8	La Niña	0	119	-5.22
9 (Weak)	La Niña	167	758	2.42

Table 11. Statistical analysis of significant relationships among phases in the MJO and TC activity in the NIO during periods of La Niña. Cells shaded red indicate a 95% significance to increased TC activity. Cells shaded blue indicate 95% significance to decreased activity.

5. Positive IOD/MJO Relationships

Analysis was performed on how specific MJO phases impact TC activity for TCs that occurred during periods of positive IOD. However, compared to the all TC sample in Table 8, the maximum positive relationship for NIO TCs during periods of positive IOD remains at phase 4, but a positive relationship no longer for phase 3 (Table 12).

During periods of a positive IOD, the most negative impact on TC activity in the NIO still occurred during phase 8 (Table 12), as was the case for the sample of all TCs.

However, the significant statistical relationship between the MJO phase 1 and decreased TC activity in the NIO no longer exists, and a significant relationship with negative TC activity is found for phase 2 over the western IO (Table 12).

MJO Phase/IOD/TC Relationship				
MJO Phase		**# TC Days**	**Total Days**	**Z-Value**
1	**+IOD**	**12**	**182**	**-1.34**
2	**+IOD**	**11**	**164**	**-1.22**
3	**+IOD**	**15**	**146**	**0.31**
4	**+IOD**	**38**	**110**	**8.95**
5	**+IOD**	**22**	**112**	**3.66**
6	**+IOD**	**5**	**126**	**-2.12**
7	**+IOD**	**8**	**163**	**-2.00**
8	**+IOD**	**4**	**184**	**-3.39**
9 (Weak)	**+IOD**	**56**	**611**	**-0.29**

Table 12. Statistical analysis of significant relationship among phases of the MJO and TC activity in the NIO during periods of positive IOD. Cells shaded red indicate a 95% significance to increased TC activity. Cells shaded blue indicate 95% significance to decreased activity.

6. Neutral IOD/MJO Relationships

Analysis was also performed on how specific MJO phases impact TC activity for TCs that occurred during periods of a neutral IOD. As was the case for all TCs (Table 8), the MJO phases 3, 4, and 5 have a significant relationship to increased activity for all NIO TCs with the maximum positive relationship with phase 4 (Table 13). Similarly, phases 7, 8, and 1 have the most statistically significant relationships to decreased TC activity in the NIO during neutral IOD periods with a minimum test statistic at phase 8 (Table 13).

MJO Phase/IOD/TC Relationship				
1	Neutral IOD	19	138	0.01
2	Neutral IOD	12	156	-2.19
3	Neutral IOD	30	115	3.85
4	Neutral IOD	38	146	4.31
5	Neutral IOD	44	176	4.34
6	Neutral IOD	17	147	-0.77
7	Neutral IOD	5	125	-3.16
8	Neutral IOD	13	102	-0.29
9 (Weak)	Neutral IOD	81	780	-2.72

Table 13. Statistical analysis of significant relationships among phases in the MJO and TC activity in the NIO during periods of neutral IOD. Cells shaded red indicate a 95% significance to increased TC activity. Cells shaded blue indicate 95% significance to decreased activity.

7. Negative IOD TCs/MJO Relationships

Analysis was also performed on how specific MJO phases impact TC activity for TCs that occurred during periods of negative IOD. Compared to the relationship to increased activity for all NIO TCs (Table 8), a statistically significant relationship no longer exists with phase 5 during periods of positive IOD (Table 14). This relationship is in contrast to TCs during positive IOD, where a significant relationship with an MJO in phase 5 over the Maritime Continent exists and does not in phase 3 over the western IO.

During negative IOD periods, the MJO phases 7, 8, and 1 were found to have statistically significant relationships with decreased TC activity in the NIO (Table 14). That is, no changes in statistical significance in relation to TC suppression over the NIO were found relative to the all TCs sample in Table 8. Thus, the impact of the MJO on NIO TC activity during the negative IOD phase is basically the same as for all TCs except for some slight shifts in preferred periods of activity or inactivity.

MJO Phase/IOD/TC Relationship

1	**-IOD**	**9**	**122**	**-3.24**
2	**-IOD**	**32**	**152**	**0.69**
3	**-IOD**	**48**	**142**	**4.55**
4	**-IOD**	**61**	**195**	**4.43**
5	**-IOD**	**48**	**223**	**1.01**
6	**-IOD**	**29**	**181**	**-0.98**
7	**-IOD**	**7**	**115**	**-3.50**
8	**-IOD**	**2**	**148**	**-5.45**
9 (Weak)	**-IOD**	**168**	**863**	**0.45**

Table 14. Statistical analysis of significant relationships among phases in the MJO and TC activity in the NIO during periods of negative IOD. Cells shaded red indicate a 95% significance to increased TC activity. Cells shaded blue indicate 95% significance to decreased activity.

8. El Niño/MJO Relationships

Analysis was performed to determine how specific MJO phases influence increased TC activity in the NIO for TCs that occurred during periods in which El Niño and a positive IOD occurred concurrently. Recall that MJO phases 3, 4, and 5 have a significant relationship to increased TC activity in the NIO TCs during El Niño periods (Table 9) but only phases 4 and 5 have a significant relationship during periods of a positive IOD (Table 12). The maximum test statistic that indicates the highest statistical significance between enhanced NIO TC activity and the MJO phase for both El Niño and positive IOD TCs occurs with phase 4 (Tables 9 and 12). When the two circulations are considered together (Table 15), MJO phases 4 and 5 were found to be statistically significant with enhanced TC activity in the NIO with phase 4 having the maximum significance.

Recall that MJO phases 6, 7, 8, 1, and weak MJOs have a significant relationship to decreased TC activity in the NIO during El Niño periods (Table 9) and phases 6, 7, and 8 during periods of a positive IOD (Table 12). The minimum test statistic that defines the highest statistical significance between decreased NIO TC activity and the MJO phase for both El Niño and positive IOD TCs is phase 8 (Tables 9 and 12). When the two circulations are considered

together (Table 15), only phase 6 was found to be statistically significant. Indeed, zero TC days occurred with this combination.

MJO Phase/El Niño/IOD TC Relationship				
MJO Phase		**# TC Days**	**Total Days**	**Z-Value**
1	**El Niño / +IOD**	**4**	**108**	**-1.83**
2	**El Niño / +IOD**	**10**	**118**	**-0.07**
3	**El Niño / +IOD**	**9**	**112**	**-0.23**
4	**El Niño / +IOD**	**22**	**62**	**7.51**
5	**El Niño / +IOD**	**9**	**50**	**2.35**
6	**El Niño / +IOD**	**0**	**58**	**-2.34**
7	**El Niño / +IOD**	**4**	**69**	**-0.84**
8	**El Niño / +IOD**	**4**	**102**	**-1.70**
9 (Weak)	**El Niño / +IOD**	**30**	**384**	**-0.59**

Table 15. Statistical analysis of significant relationships among phases in the MJO and TC activity in the NIO during periods of El Niño in conjunction with positive IOD. Cells shaded red indicate a 95% significance to increased TC activity. Cells shaded blue indicate 95% significance to decreased activity.

Recall that MJO phases 3, 4, and 5 have a significant relationship to increased TC activity in the NIO TCs during periods of El Niño (Table 9) and a neutral IOD (Tables 13). When the periods in which El Niño and a neutral IOD occurred in conjunction, the significant relationship no longer existed for phases 3 and 5 (Table 16). Only for an MJO in the region of the Maritime Continent (phase 4) was a statistically significant relationship to increased TC activity in the NIO found. Because the maximum test statistic for El Niño was in phase 4 and for neutral IOD was in phase 5, it is hypothesized the influence of El Niño on the MJO phase may have a more dominate effect in the NIO TC activity enhancement.

Recall that MJO phases 6, 7, 8, 1, and weak MJOs have a significant relationship to decreased NIO TC activity during El Niño (Table 9) and only phases 7, 2, and weak MJOs during periods of a neutral IOD (Table 13). The minimum test statistics that indicate the highest statistical significance are phase 8 (Table 9) and phase 7 during a neutral IOD (Table 13). When El Niño and a

neutral IOD occurred in conjunction, no statistical significant relationships were found (Table 16).

MJO Phase/El Niño/IOD TC Relationship				
1	El Niño / Neutral IOD	1	43	-1.78
2	El Niño / Neutral IOD	4	38	-0.03
3	El Niño / Neutral IOD	7	46	0.99
4	El Niño / Neutral IOD	14	52	3.78
5	El Niño / Neutral IOD	8	51	1.15
6	El Niño / Neutral IOD	5	39	0.43
7	El Niño / Neutral IOD	0	24	-1.70
8	El Niño / Neutral IOD	0	18	-1.47
9 (Weak)	El Niño / Neutral IOD	19	231	-1.22

Table 16. Statistical analysis of significant relationships among phases in the MJO and TC activity in the NIO during periods of El Niño in conjunction with neutral IOD. Cells shaded red indicate a 95% significance to increased TC activity. Cells shaded blue indicate 95% significance to decreased activity.

Recall that MJO phases 3, 4, and 5 have a significant relationship to increased TC activity in the NIO TCs during periods of El Niño (Table 9) and only phases 3 and 4 for a negative IOD (Table 14). The maximum test statistics that indicate the highest statistical significance are phase 4 (Table 9) and phase 3 for periods of a negative IOD TCs (Table 14). When the two circulations are considered together (Table 17), statistically significant relationships were found in phases 2, 3 and 4, with phase 3 having the maximum significance. Given that the maximum test statistic for negative IOD was phase 3, this may indicate a stronger influence from the negative IOD on the MJO phase that leads to NIO TC activity enhancement.

Considering periods in which El Niño and a negative IOD occurred concurrently, the minimum test statistic for both conditions individually leading to decreased NIO TC activity is in phase 8 (Tables 9 and 14). When the El Niño periods and a negative IOD occurred in conjunction, phases 6, 8, and weak MJOs were found to have statistically significant relationships, with weak MJOs having the maximum significance (Table 17). Therefore the combination of the

El Niño and negative IOD, both of which have a negative impact on NIO TC activity, expanded the phases of MJO influence that lead to decreased NIO TC activity.

MJO Phase/El Niño/IOD TC Relationship				
1	El Niño / -IOD	2	24	-1.24
2	El Niño / -IOD	12	30	3.12
3	El Niño / -IOD	26	58	5.29
4	El Niño / -IOD	22	53	4.43
5	El Niño / -IOD	6	42	-0.64
6	El Niño / -IOD	1	30	-2.10
7	El Niño / -IOD	2	18	-0.77
8	El Niño / -IOD	0	27	-2.44
9 (Weak)	El Niño / -IOD	6	144	-4.34

Table 17. Statistical analysis of significant relationships among phases in the MJO and TC activity in the NIO during periods of El Niño in conjunction with negative IOD. Cells shaded red indicate a 95% significance to increased TC activity. Cells shaded blue indicate 95% significance to decreased activity.

9. Neutral ENSO/MJO Relationships

A similar analysis is performed to MJO impacts in conjunction with neutral ENSO and the three IOD phases. Recall that MJO phases 3 and 4 have a significant relationship to increased TC activity in the NIO TCs during periods of a neutral ENSO (Table 10) and phases 4 and 5 during periods of a positive IOD (Table 12). When the neutral ENSO and a positive IOD occurred in conjunction, only MJO phase 4 was found to be statistically significant (Table 18). Although the maximum test statistic for neutral ENSO was phase 3 and positive IOD was phase 4, it is likely that phase 4 has the maximum test statistic as it was common to both conditions.

Phase 7 of the MJO is the only phase that has a significant relationship to decreased TC activity in the NIO during periods of neutral ENSO (Table 10) and phases 6, 7, and 8 during periods of a positive IOD (Table 12). When the neutral ENSO and positive IOD occurred in conjunction, only phase 8 was found to be statistically significant (Table 18). Indeed, zero TCs occurred with this

combination of conditions. Because the minimum test statistic for positive IOD was phase 8 and neutral ENSO was phase 7, it is hypothesized that the influence of positive IOD on MJO phase dominates over the influence of neutral ENSO.

MJO Phase/Neutral ENSO/IOD TC Relationship				
MJO Phase		**# TC Days**	**Total Days**	**Z-Value**
1	**Neutral ENSO / +IOD**	**1**	**54**	**-1.51**
2	**Neutral ENSO / +IOD**	**0**	**46**	**-1.88**
3	**Neutral ENSO / +IOD**	**4**	**27**	**1.55**
4	**Neutral ENSO / +IOD**	**6**	**27**	**3.04**
5	**Neutral ENSO / +IOD**	**3**	**19**	**1.46**
6	**Neutral ENSO / +IOD**	**4**	**42**	**0.60**
7	**Neutral ENSO / +IOD**	**4**	**70**	**-0.46**
8	**Neutral ENSO / +IOD**	**0**	**61**	**-2.17**
9 (Weak)	**Neutral ENSO / +IOD**	**13**	**144**	**0.88**

Table 18. Statistical analysis of significant relationships among phases in the MJO and TC activity in the NIO during periods of neutral ENSO in conjunction with positive IOD. Cells shaded red indicate a 95% significance to increased TC activity. Cells shaded blue indicate 95% significance to decreased activity.

The MJO phases 3 and 4 have a significant relationship to increased TC activity in the NIO TCs during periods of neutral ENSO (Table 10) and phases 3, 4 and 5 for periods of a neutral IOD (Table 13). The maximum test statistic that defines the highest statistical significance between enhanced NIO TC activity and the MJO phase for periods of neutral ENSO is phase 3 (Table 10) and phase 5 for periods of a neutral IOD (Table 13). When the neutral ENSO and neutral IOD occurred in conjunction, a significant relationship exists with phases 3, 4, 5, and 8, with phase 3 having the greatest significance (Table 19). The neutral ENSO and neutral DMI was the only ENSO/DMI combination that resulted in a positive TC impact during MJO phase 8. For the sample of TCs, phase 8 was found to have the most negative relationship (Table 8). The physical factors leading to the relationship between enhanced NIO TC activity and an MJO in phase 8 during periods of neutral ENSO and IOD are unknown.

The MJO phase 7 was the only MJO phase to have a significant relationship to decreased NIO TC activity during periods of neutral ENSO (Table 10) and phases 7, 2, and weak MJOs during periods of a neutral IOD (Table 13). When the neutral ENSO and IOD occurred in conjunction, a significant negative relationship exists only for weak MJOs (Table 19). However, 18 TC days occurred out of a total of 289 days with this condition. It is hypothesized the influence of neutral IOD on MJO phase dominates over the influence of neutral ENSO in cases of NIO TC activity suppression because only neutral IOD was found to have a significant statistical relationship with weak MJOs and decreased TC activity.

MJO Phase/Neutral ENSO/IOD TC Relationship				
1	Neutral ENSO / Neutral IOD	16	64	2.13
2	Neutral ENSO / Neutral IOD	7	68	-1.16
3	Neutral ENSO / Neutral IOD	17	45	4.16
4	Neutral ENSO / Neutral IOD	11	38	2.32
5	Neutral ENSO / Neutral IOD	19	60	3.50
6	Neutral ENSO / Neutral IOD	4	48	-1.35
7	Neutral ENSO / Neutral IOD	3	39	-1.33
8	Neutral ENSO / Neutral IOD	13	51	2.00
9 (Weak)	Neutral ENSO / Neutral IOD	18	289	-4.31

Table 19. Statistical analysis of significant relationships among phases in the MJO and TC activity in the NIO during periods of neutral ENSO in conjunction with neutral IOD. Cells shaded red indicate a 95% significance to increased TC activity. Cells shaded blue indicate 95% significance to decreased activity.

The maximum test statistic between enhanced NIO TC activity and the MJO phase for periods of neutral ENSO and negative IOD is phase 3 (Tables 10 and 14). However, no significant relationship was found (Table 20) when the periods of neutral ENSO and a negative IOD occurred in conjunction.

The MJO phase 7 is the only MJO phase to have a significant relationship to decreased TC activity during periods of neutral ENSO (Table 10) and phases 7, 8, and 1 during periods of a negative IOD (Table 14). When the neutral ENSO and a positive IOD occurred in conjunction, phases 5 and 8 were found to be

statistically significant with phase 5 having the maximum significance (Table 20). However, the test statistic for phase 8 barely met the significance criterion, and only one more TC day would have reduced the test statistic below the criterion.

MJO Phase/Neutral ENSO/IOD TC Relationship				
1	Neutral ENSO / -IOD	5	37	0.22
2	Neutral ENSO / -IOD	13	65	1.89
3	Neutral ENSO / -IOD	7	38	1.15
4	Neutral ENSO / -IOD	10	55	1.32
5	Neutral ENSO / -IOD	1	56	-2.40
6	Neutral ENSO / -IOD	3	39	-0.88
7	Neutral ENSO / -IOD	3	52	-1.44
8	Neutral ENSO / -IOD	2	56	-1.99
9 (Weak)	Neutral ENSO / -IOD	39	276	0.92

Table 20. Statistical analysis of significant relationships among phases in the MJO and TC activity in the NIO during periods of neutral ENSO in conjunction with negative IOD. Cells shaded red indicate a 95% significance to increased TC activity. Cells shaded blue indicate 95% significance to decreased activity.

10. La Niña/MJO Relationships

The MJO phases 4, 5, and weak MJOs have a significant relationship to increased TC activity in the NIO TCs during La Niña periods (Table 11) and phases 4 and 5 during periods of a positive IOD (Table 12). When the La Niña and a positive IOD occurred in conjunction, no significant relationship was found (Table 21).

Phases 7, 8, 1, and 2 of the MJO have a significant relationship to decreased TC activity in the NIO during periods of La Niña (Table 11) and phases 6, 7, and 8 during periods of a positive IOD (Table 12). When the La Niña and a positive IOD occurred in conjunction, phases 7 and 8 were found to be statistically significant, with phase 8 having the maximum significance (Table 20). No TCs occurred in these two sets of conditions.

MJO Phase/La Niña/IOD TC Relationship

MJO Phase		# TC Days	Total Days	Z-Value
1	La Niña / +IOD	7	23	1.83
2	La Niña / +IOD	1	12	-0.75
3	La Niña / +IOD	0	5	-0.99
4	La Niña / +IOD	4	13	1.41
5	La Niña / +IOD	10	36	1.85
6	La Niña / +IOD	1	21	-1.44
7	La Niña / +IOD	0	20	-1.98
8	La Niña / +IOD	0	21	-2.03
9 (Weak)	La Niña / +IOD	12	63	0.58

Table 21. Statistical analysis of significant relationships among phases in the MJO and TC activity in the NIO during periods of La Niña in conjunction with positive IOD. Cells shaded red indicate a 95% significance to increased TC activity. Cells shaded blue indicate 95% significance to decreased activity.

The MJO phases 4, and 5 have a significant relationship to increased TC activity in the NIO during periods of La Niña and phases 3, 4, and 5 during periods of a neutral IOD (Tables 11 and 13). When the La Niña and a neutral IOD occurred in conjunction, phase 4 was the only phase found to be statistically significant (Table 22).

The MJO phases 7, 8, 1, 2 have a significant relationship to decreased TC activity in the NIO during periods of La Niña (Table 11) and phases 7, 2, and weak MJOs during periods of a neutral IOD (Table 13). When the neutral ENSO and IOD occurred in conjunction, no significant relationship was found even though no TCs occurred in phases 7 and 8 (Table 22).

MJO Phase/La Niña/IOD TC Relationship				
1	La Niña / Neutral IOD	3	50	-1.20
2	La Niña / Neutral IOD	5	52	-0.40
3	La Niña / Neutral IOD	7	46	0.82
4	La Niña / Neutral IOD	14	52	3.54
5	La Niña / Neutral IOD	8	51	0.97
6	La Niña / Neutral IOD	5	39	0.29
7	La Niña / Neutral IOD	0	24	-1.75
8	La Niña / Neutral IOD	0	18	-1.52
9 (Weak)	La Niña / Neutral IOD	23	240	-0.87

Table 22. Statistical analysis of significant relationships among phases in the MJO and TC activity in the NIO during periods of La Niña in conjunction with neutral IOD. Cells shaded red indicate a 95% significance to increased TC activity. Cells shaded blue indicate 95% significance to decreased activity.

The MJO phases 4 and 5 have a significant relationship to increased TC activity in the NIO TCs during periods of La Niña (Table 11) and phases 3 and 4 for a negative IOD (Table 14). When the La Niña and a negative IOD occurred in conjunction, phase 5 was the only MJO phase found to be statistically significant (Table 23). However, the test statistic for phase 5 barely met the significance criterion.

The MJO phases 7, 8, 1, and 2 have a significant relationship to decreased TC activity in the NIO TCs with periods of La Niña (Table 11) and only phases 7, 8, and 1 during periods of a negative IOD (Table 14). When the La Niña and a positive IOD occurred in conjunction, phases 7, 8, and 1 were found to be statistically significant with phase 8 having the maximum significance (Table 23).

MJO Phase/La Niña/IOD TC Relationship				
1	La Niña / -IOD	2	61	-3.54
2	La Niña / -IOD	7	57	-1.78
3	La Niña / -IOD	13	44	1.19
4	La Niña / -IOD	24	79	1.78
5	La Niña / -IOD	35	118	1.99
6	La Niña / -IOD	25	108	0.27
7	La Niña / -IOD	2	43	-2.76
8	La Niña / -IOD	0	65	-4.29
Weak	La Niña / -IOD	115	435	2.19

Table 23. Statistical analysis of significant relationships among phases in the MJO and TC activity in the NIO during periods of La Niña in conjunction with negative IOD. Cells shaded red indicate a 95% significance to increased TC activity. Cells shaded blue indicate 95% significance to decreased activity.

D. MJO/ENSO/IOD RELATIONSHIP WITH TC ACTIVITY

As previously defined, a "convective MJO" will be designated as having an index magnitude of one or greater in phases 3, 4, or 5. A "non-convective MJO" will be an MJO with magnitude of one or greater in phases 7, 8, or 1. A "weak MJO" will be defined as having a magnitude of less than one.

1. ENSO and Convective MJO

As previously stated in relation to TC activity in the NIO, La Niña is found to be related to increased activity, periods of neutral ENSO are related to decreased activity, and no significant relationship exists with El Niño (Table 5). When a convective MJO occurs during any of the three ENSO phases, a statistically significant relationship exists between increased TC activity in the NIO (Table 24). The convective MJO occurrence increases the La Niña impact on TC enhancement and overrides the negative impacts on TC activity of the neutral ENSO. In addition, when a convective MJO occurs during periods of El Niño, the largest statistical significance resulted among any of the IOD/ENSO/MJO phase combinations (Table 24).

2. IOD and Convective MJO

A negative IOD is related to increased TC activity, positive IOD is related to decreased activity, and no relationship exists between TC activity and the neutral IOD (Table 5). The effect of the convective MJO increased the negative IOD impact on increased TC activity and alters the negative impact on TC activity during the negative IOD (Table 24). When a convective MJO occurs during a neutral IOD, the fourth highest statistical significance among any of the IOD/ENSO/MJO phase combinations resulted.

3. ENSO and IOD with a Convective MJO

Both positive and neutral IOD conditions in conjunction with El Niño are related to statistically significant decreased TC activity (Table 5). However, when a positive IOD or neutral IOD occurs during El Niño periods, and a convective MJO is also present, the negative effect from the ENSO and IOD combination counteracts the positive impact from the convective MJO. That is, no statistically significant relationship with TC activity is found in these conditions (Table 24).

Previous results indicate that when El Niño periods occurred in conjunction with a negative IOD, a significant statistical relationship with increased TC activity in the NIO occurs (Table 5). When a convective MJO is also present during periods of El Niño with a negative IOD, the TC activity is enhanced and leads to the second highest statistically significant relationship among all phase combinations from ENSO, IOD, and MJO (Table 24).

A combination of a positive IOD and neutral ENSO conditions has a significant relationship to decreased TC activity in the NIO (Table 5). When a positive IOD occurs during neutral ENSO periods, and a convective MJO is also present, the negative effect from the ENSO/IOD combination is offset by the convective MJO and a statistically significant relationship exists with increased TC activity in the NIO (Table 24).

Periods of neutral ENSO that occur in conjunction with a neutral IOD have no significant statistical relationship with increased or decreased TC activity in

the NIO (Table 5). When a convective MJO is present during periods of neutral ENSO with a neutral IOD, a statistically significant relationship exists with increased TC activity in the NIO (Table 24).

Periods of neutral ENSO that occur in conjunction with a negative IOD also had no significant statistical relationship with increased or decreased TC activity in the NIO (Table 5). When a convective MJO is present during periods of neutral ENSO and a negative IOD, the impact of the convective MJO was not large enough to define a significant relationship to increased TC activity in the NIO (Table 24).

A positive IOD and a neutral IOD during periods of La Niña have no statistically significant relationship to TC activity in the NIO (Table 5). When a positive IOD or neutral IOD occurs during La Niña periods, and a convective MJO is present, no significant relationship to TC activity is found (Table 24).

Periods of La Niña that occur in conjunction with a negative IOD have the highest significant statistical relationship with increased TC activity in the NIO of any IOD/ENSO phase combination (Table 5). When a convective MJO is also present during periods of La Niña and a negative IOD, a statistically significant relationship still exists with increased TC activity, but the level of significance is a bit lower (Table 24).

Based on the above, it is concluded the convective phase of the MJO provides the most significant impacts on TC activity in the NIO during periods of El Niño and neutral ENSO. During periods of La Niña, the convective MJO has little impact. It may also be concluded that the convective MJO is more significant during periods of positive and neutral ENSO than during periods of a negative IOD. Therefore, the southwest Pacific warm pool that is anomalously warm during La Niña and negative IOD may have a larger influence on TC activity in the NIO than does the convective phases of the MJO.

ENSO/DMI/MJO Relationship to TCs in NIO			TC Days	Total Days	Z-Value
El Niño only		Convective MJO	134	551	8.91
Neutral ENSO only		Convective MJO	77	382	5.58
La Niña only		Convective MJO	116	440	4.30
+IOD only		Convective MJO	71	368	3.50
Neutral IOD only		Convective MJO	102	437	6.32
-IOD only		Convective MJO	152	561	5.81
El Niño	+IOD	Convective MJO	42	232	0.64
El Niño	Neutral IOD	Convective MJO	26	149	0.30
El Niño	-IOD	Convective MJO	66	170	7.82
Neutral ENSO	+IOD	Convective MJO	18	89	2.95
Neutral ENSO	Neutral IOD	Convective MJO	41	143	7.02
Neutral ENSO	-IOD	Convective MJO	18	150	0.56
La Niña	+IOD	Convective MJO	13	54	0.57
La Niña	Neutral IOD	Convective MJO	35	145	0.95
La Niña	-IOD	Convective MJO	68	241	2.78

Table 24. Statistical analysis of significant relationships among phases and combinations of ENSO and IOD and the convective MJO. Cells shaded red indicate a 95% significance to increased TC activity. Cells shaded blue indicate 95% significance to decreased activity.

4. ENSO and Non-Convective MJO

When a non-convective MJO occurs during any of the three ENSO phases, a statistically significant relationship exists with decreased TC activity in the NIO (Table 25). The effect of the non-convective MJO during periods of La Niña was the strongest. That is, the negative aspect of the non-convective MJO even overrides the significantly positive aspect of La Niña (Table 25).

5. IOD and Non-Convective MJO

When a non-convective MJO occurs during any of the three IOD phases, a statistically significant negative impact on TC activity occurs in the NIO (Table 25). As found in relationship to ENSO, the non-convective MJO has the most significant impact on negative IOD, which changes the positive impact of the negative IOD to a negative impact (Table 25).

6. ENSO and IOD and Non-Convective MJO

When a positive IOD or neutral IOD occurs during El Niño periods, and a non-convective MJO is present, the negative effect from the ENSO these two IOD phases combines with the negative TC impact from the non-convective MJO to result in an increased statistical relationship to decreased TC activity in the NIO (Table 25). When a non-convective MJO is present during periods of El Niño and a negative IOD, the influence of the non-convective MJO results in a stronger relationship to decreased TC activity in the NIO (Table 25).

When a positive IOD occurs during neutral ENSO periods, and a non-convective MJO is present, the negative effect from the ENSO/IOD combination is enhanced by the non-convective MJO and there is a more significant relationship to decreased TC activity in the NIO (Table 25). When a non-convective MJO is present during periods of neutral ENSO and a neutral IOD or positive IOD, no significant relationship to NIO TC activity was found (Table 25).

When a positive IOD or neutral IOD occurs during La Niña periods, and a non-convective MJO is present, the negative impact of the non-convective MJO dominates the statistically significant relationship with decreased TC activity in the NIO (Table 25). When a non-convective MJO is present during periods of La Niña, and a negative IOD, a statistically significant relationship exists with decreased TC activity in the NIO.

It is concluded that the negative influence on TC activity from the non-convective phases of the MJO is only altered during periods of neutral ENSO and neutral IOD and neutral ENSO and negative IOD combinations. One of the largest statistical significances on decreased TC activity with an MJO in a non-convective phase was with La Niña and negative IOD, which are normally related to increased TC activity (Table 5).

ENSO/DMI/MJO Relationship to TCs in NIO					
			TC Days	Total Days	Z-Value
El Niño only		**Non-Convective MJO**	**17**	**435**	**-5.19**
Neutral ENSO only		**Non-Convective MJO**	**37**	**492**	**-2.57**
La Niña only		**Non-Convective MJO**	**15**	**359**	**-6.96**
+IOD only		**Non-Convective MJO**	**24**	**529**	**-5.85**
Neutral IOD only		**Non-Convective MJO**	**28**	**365**	**-3.09**
-IOD only		**Non-Convective MJO**	**17**	**389**	**-6.90**
El Niño	**+IOD**	**Non-Convective MJO**	**12**	**279**	**-5.50**
El Niño	**Neutral IOD**	**Non-Convective MJO**	**1**	**85**	**-3.81**
El Niño	**-IOD**	**Non-Convective MJO**	**17**	**389**	**-6.46**
Neutral ENSO	**+IOD**	**Non-Convective MJO**	**5**	**189**	**-3.55**
Neutral ENSO	**Neutral IOD**	**Non-Convective MJO**	**23**	**154**	**1.75**
Neutral ENSO	**-IOD**	**Non-Convective MJO**	**9**	**159**	**-1.81**
La Niña	**+IOD**	**Non-Convective MJO**	**7**	**64**	**-1.96**
La Niña	**Neutral IOD**	**Non-Convective MJO**	**4**	**126**	**-4.90**
La Niña	**-IOD**	**Non-Convective MJO**	**4**	**169**	**-5.93**

Table 25. Statistical analysis of significant relationships among phases and combinations of ENSO and IOD and the non-convective MJO. Cells shaded red indicate a 95% significance to increased TC activity. Cells shaded blue indicate 95% significance to decreased activity.

7. ENSO and Weak MJO

When a weak MJO (i.e., index value less than 1.0) occurs during La Niña, the significant impact of La Niña on increased TC activity in the NIO is no longer present (Table 26). When the MJO is weak (Table 26), there is still a statistical relationship between neutral ENSO and decreased TC activity in the NIO. Although, El Niño was found not to have a statistical relationship to NIO TC activity, a statistically significant relationship exists between decreased TC activity in the NIO and El Niño periods when the MJO is weak (Table 26).

8. IOD and Weak MJO

When the MJO is weak, a statistically significant relationship to decreased NIO TC activity exists during periods of positive IOD and neutral IOD (Table 26). When the IOD is negative, a weak MJO suppresses the positive influence of the negative IOD (Table 26).

9. ENSO and IOD and Weak MJO

When a positive IOD or neutral IOD occurs during El Niño periods and the MJO is weak, the negative impact on NIO TC activity of the IOD/El Niño conditions is increased (Table 26). Recall that periods of El Niño in conjunction with a negative IOD have a significant statistical relationship with increased TC activity (Table 5). However, during periods of El Niño, and a negative IOD when the MJO is weak, the relationship to TC activity in the NIO is no longer significant (Table 26).

A positive IOD during periods of neutral ENSO has a significant relationship to decreased TC activity in the NIO (Table 5). When a positive IOD occurs during neutral ENSO periods and the MJO is weak, the relationship to TC activity in the NIO is no longer significant (Table 26).

A neutral ENSO in conjunction with a neutral IOD has no significant statistical relationship with increased or decreased TC activity in the NIO (Table 5). When the MJO is weak during periods of neutral ENSO with a neutral IOD, a significant negative impact on TC activity in the NIO is found (Table 26).

Periods of neutral ENSO that occurred in conjunction with a positive IOD have no significant statistical relationship with increased or decreased TC activity in the NIO (Table 5). When the MJO is weak during periods of neutral ENSO with a positive IOD, no change in the relationship to NIO TC activity was found (Table 26).

A positive IOD and a neutral IOD during periods of La Niña results in no statistically significant in relationships to TC activity in the NIO (Table 5). This

lack of a relationship with TC activity does not change when a weak MJO also occurs during the positive and neutral IOD during La Niña (Table 26).

Periods of La Niña that occur in conjunction with a negative IOD have the highest significant relationship with increased TC activity in the NIO of any IOD/ENSO phase combination (Table 5). When the MJO is weak during periods of La Niña with a negative IOD, the statistically significant relationship to increased TC activity no longer exists (Table 26).

One can conclude the MJO in a weak phase tends to dampen the impact of ENSO and IOD on TC activity in the NIO. This damping was most evident in the positive impacts of El Niño/negative IOD and La Niña/ negative IOD, as well as the suppressed TC activity in the neutral ENSO/positive IOD combination. A weak MJO in conjunction with the El Niño/positive IOD combination made the statistical relationship with decreased TC activity in the NIO even more significant.

ENSO/DMI/MJO Relationship to TCs in NIO					
			TC Days	Total Days	Z-Value
El Niño only		Weak MJO	63	799	-3.57
Neutral ENSO only		Weak MJO	62	702	-1.96
La Niña only		Weak MJO	155	754	1.63
+IOD only		Weak MJO	55	611	-3.02
Neutral IOD only		Weak MJO	79	790	-2.60
-IOD only		Weak MJO	150	850	-0.06
El Niño	+IOD	Weak MJO	31	406	-4.83
El Niño	Neutral IOD	Weak MJO	19	241	-3.62
El Niño	-IOD	Weak MJO	150	850	0.87
Neutral ENSO	+IOD	Weak MJO	13	146	-0.67
Neutral ENSO	Neutral IOD	Weak MJO	16	289	-2.80
Neutral ENSO	-IOD	Weak MJO	33	267	0.93
La Niña	+IOD	Weak MJO	11	63	-0.68
La Niña	Neutral IOD	Weak MJO	44	260	-1.59
La Niña	-IOD	Weak MJO	104	431	1.63

Table 26. Statistical significance between different phases and combinations of ENSO and IOD and the weak MJO. Cell shaded red indicates a 95% significance to increased TC activity. Cell shaded blue indicates 95% decreased activity.

E. LOW-LEVEL WINDS AND CONVECTIVE PRECIPITATION

1. ENSO Composites

The ENSO phases with the most statistically significant relationships were examined to define the low-level features related to the statistical character of the large-scale environment and TC activity. For example, La Niña is the ENSO phase with the most statistically significant relationship to increased NIO TC activity and neutral ENSO has the most significant relationship to decreased activity (Table 5). Thus, periods of La Niña and neutral ENSO are analyzed for only the months of the two NIO TC seasons. Composites of the zonal component of the 850 hPa wind (U850) will represent the low-level winds and composites of convective precipitation will represent low-level moisture.

Westerly U850 winds are more uniform and widespread throughout the entire NIO during neutral ENSO periods (Figure 14a) than during La Niña (Figure 14b). During La Niña, the tropical easterlies from the west Pacific extend into the northern BoB and interact with the strong equatorial westerlies to increase a background cyclonic flow in the eastern IO (Figure 14b). Differences between these two composites indicate statistically significantly more anticyclonic (cyclonic) flow throughout the NIO during neutral ENSO (La Niña) (Figure 14c). These composites are consistent with the statistical relationships between neutral ENSO (La Niña) and decreased (increased) TC activity in the NIO.

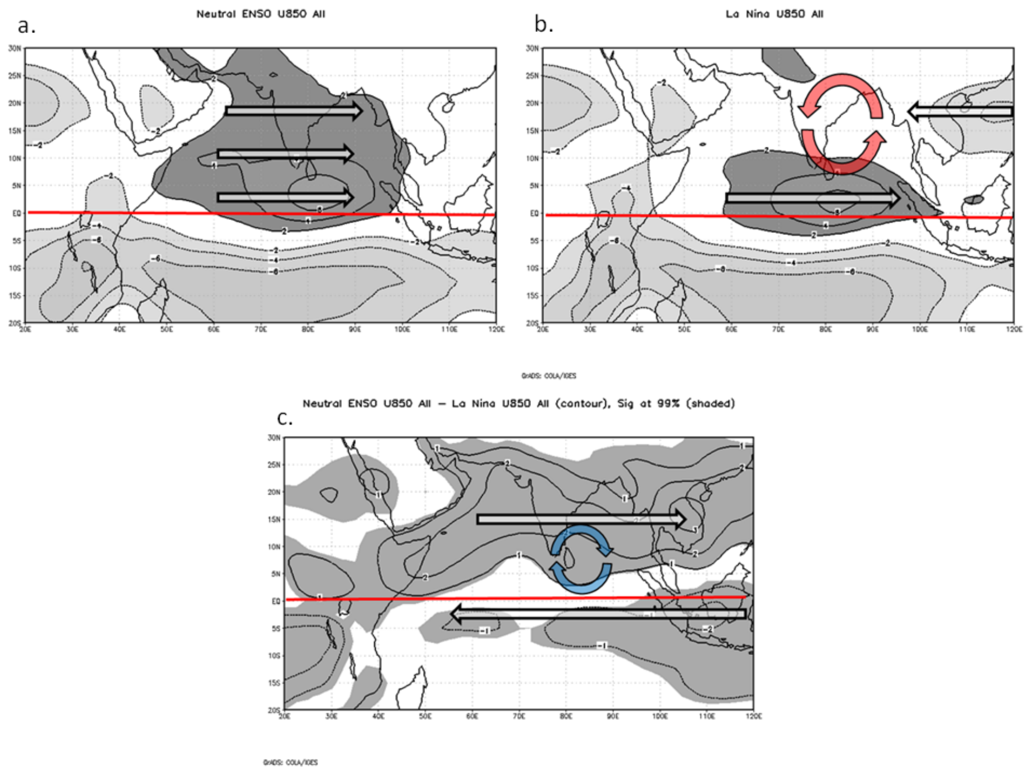

Figure 14. Composite U850 winds (m s^{-1}) during periods of: (a) neutral ENSO, (b) La Niña, and (c) neutral ENSO - La Niña. Shaded areas define 99% statistical significance.

Significantly more convective precipitation exists across most of the NIO during La Niña than neutral ENSO (Figure 15c) with maxima off the southwest coast of India and over the Maritime Continent. These patterns are consistent with the distribution of zonal wind and support the statistical relationship previously found between neutral ENSO (La Niña) and decreased (increased) TC activity in the NIO (Table 5).

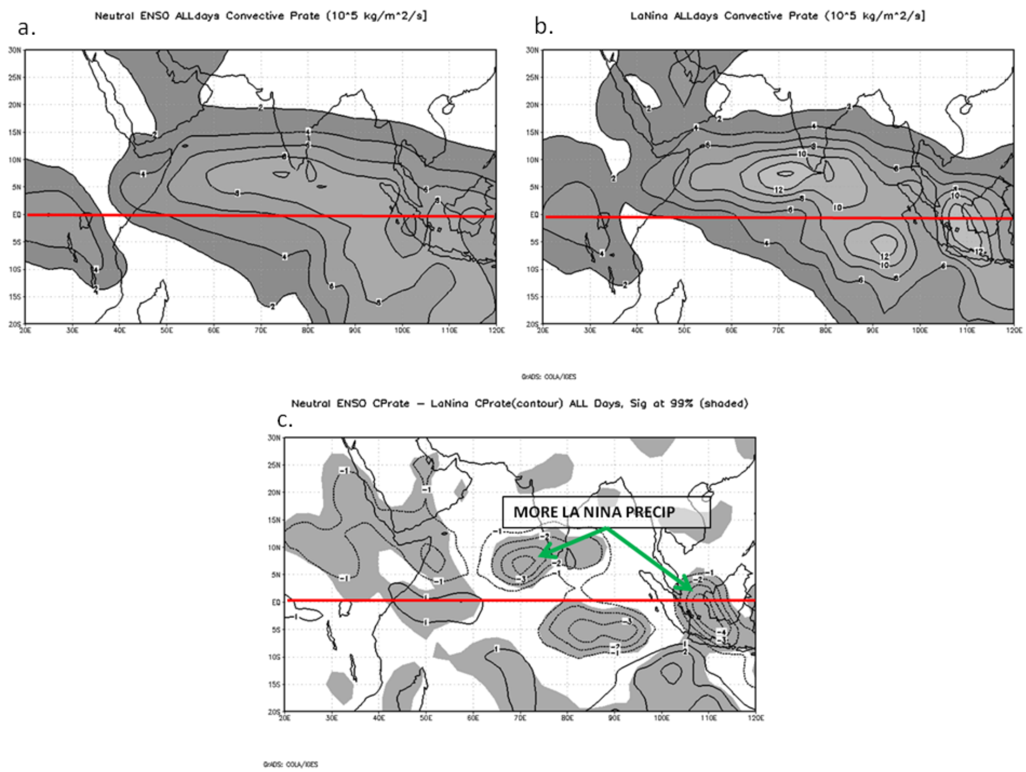

Figure 15. Composite convective precipitation (10^{-5} kg m^{-2} s^{-1}) during periods of: (a) neutral ENSO, (b) La Niña, and (c) neutral ENSO - La Niña. Shaded areas define 99% statistical significance.

2. IOD Composites

Negative IOD is the IOD phase with the most statistically significant relationship with increased NIO TC activity and positive IOD has the most significant relationship with decreased activity (Table 5). Westerly U850 winds are more uniform and widespread throughout the entire NIO during positive IOD periods (Figure 16a) than during negative IOD. During negative IOD periods, the tropical easterlies in the west Pacific extend into the northern BoB and interact with the strong equatorial westerlies to influence cyclonic flow in the eastern IO. Differences between these two composites indicate statistically significantly more background anticyclonic (cyclonic) flow throughout the NIO during positive IOD (negative IOD) (Figure 16c). These findings support the statistical relationship previously found between positive IOD (negative IOD) and decreased

(increased) TC activity in the NIO (Table 5). The similarity between the IOD (Figure 16) and ENSO (Figure 14) composites reflect the consistency in the ENSO and IOD in effecting NIO TC activity.

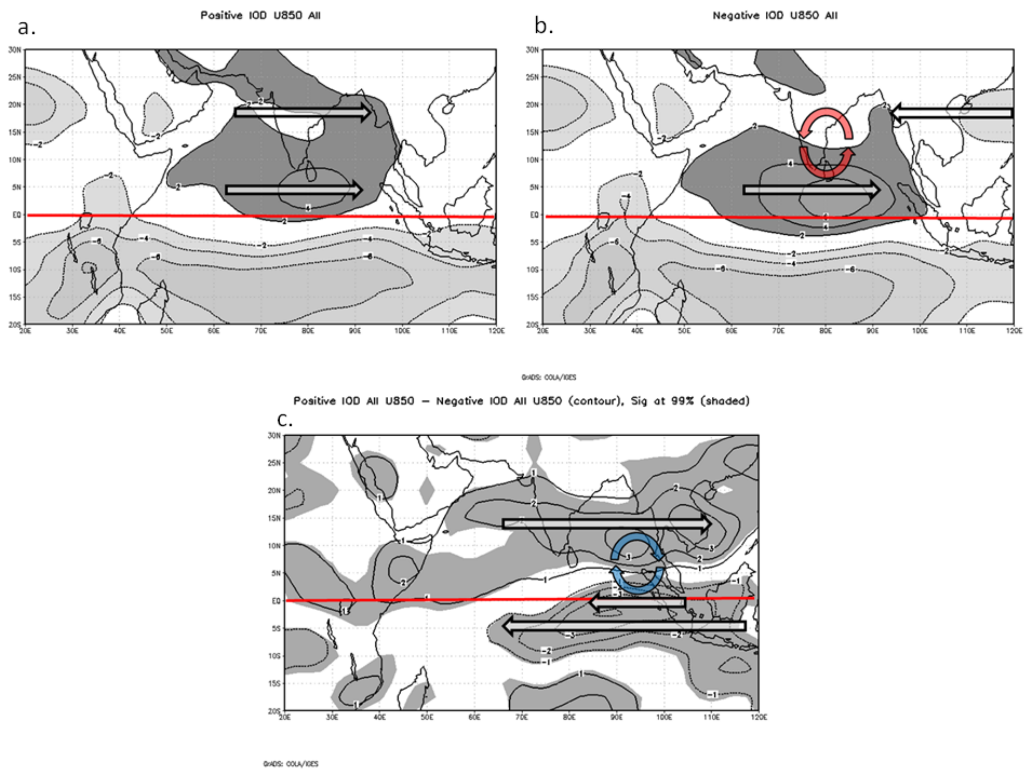

Figure 16. Composite U850 winds (m s^{-1}) during periods of: (a) positive IOD, (b) negative IOD, and (c) positive IOD - negative IOD. Shaded areas define 99% statistical significance.

Convective precipitation is significantly enhanced over the south BoB (Figure 17c) during the negative IOD. A maximum exists off the Sri Lankan east coast when the IOD is negative (Figure 17b). During positive IOD periods, significantly more convective precipitation occurs off east Africa (Figure 17a). These distributions are consistent with the statistical relationships between negative IOD (positive IOD) and increased (decreased) TC activity in the NIO with more than twice as many TCs in the BoB compared to the AS (Tables 6 and 7).

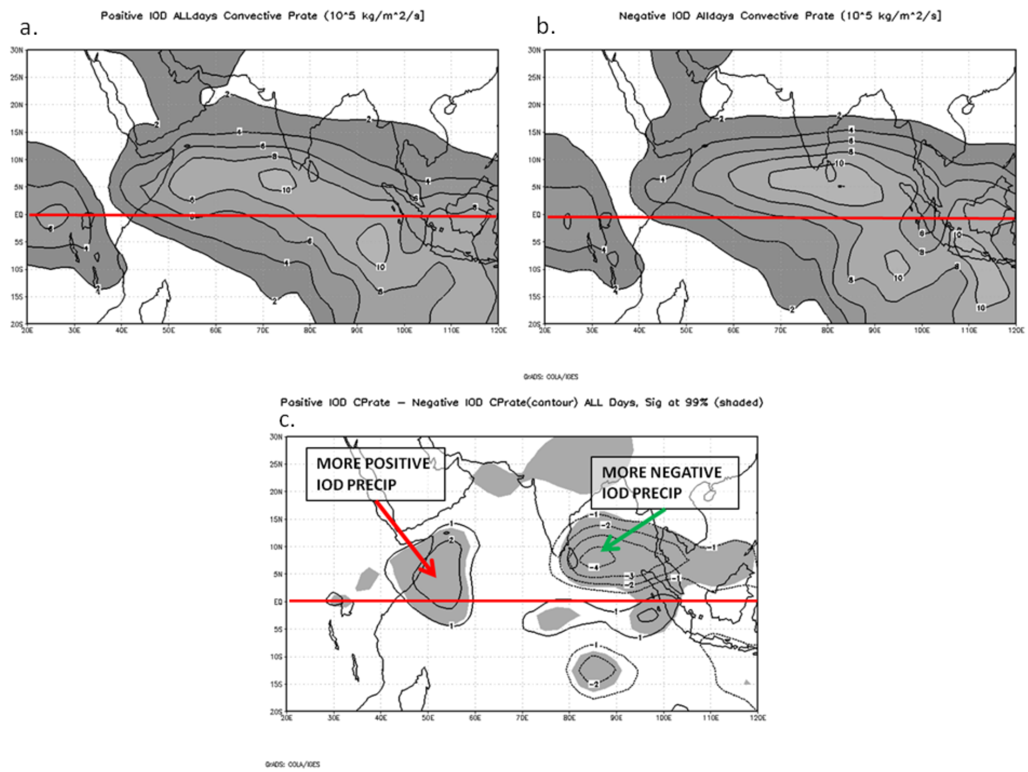

Figure 17. Composite convective precipitation (10^{-5} kg m^{-2} s^{-1}) during periods of: (a) positive IOD, (b) negative IOD, and (c) positive IOD - negative IOD. Shaded areas define 99% statistical significance.

3. MJO Composites

Convective MJO phases 3, 4, and 5 have the most statistically significant relationship to increased NIO TC activity and non-convective MJO phases 7, 8, and 1 have the most significant relationship to decreased activity (Table 8). Composites for positive and negative MJO days were made using only the months of the two NIO TC seasons.

Tropical easterlies from the west Pacific extend into the northern BoB and interact with the strong equatorial westerlies to influence cyclonic flow in the eastern IO when the MJO is positive (Figure 18a). Westerly U850 wind anomolies are weaker and widespread over the NIO and northern India when the MJO is negative (Figure 18b). Differences between these two composites indicate significantly more cyclonic (anticyclonic) background flow throughout the

NIO when the MJO is positive (negative) (Figure 18c). These findings support the statistical relationships previously found between positive MJO (negative MJO) and increased (decreased) TC activity in the NIO (Table 8).

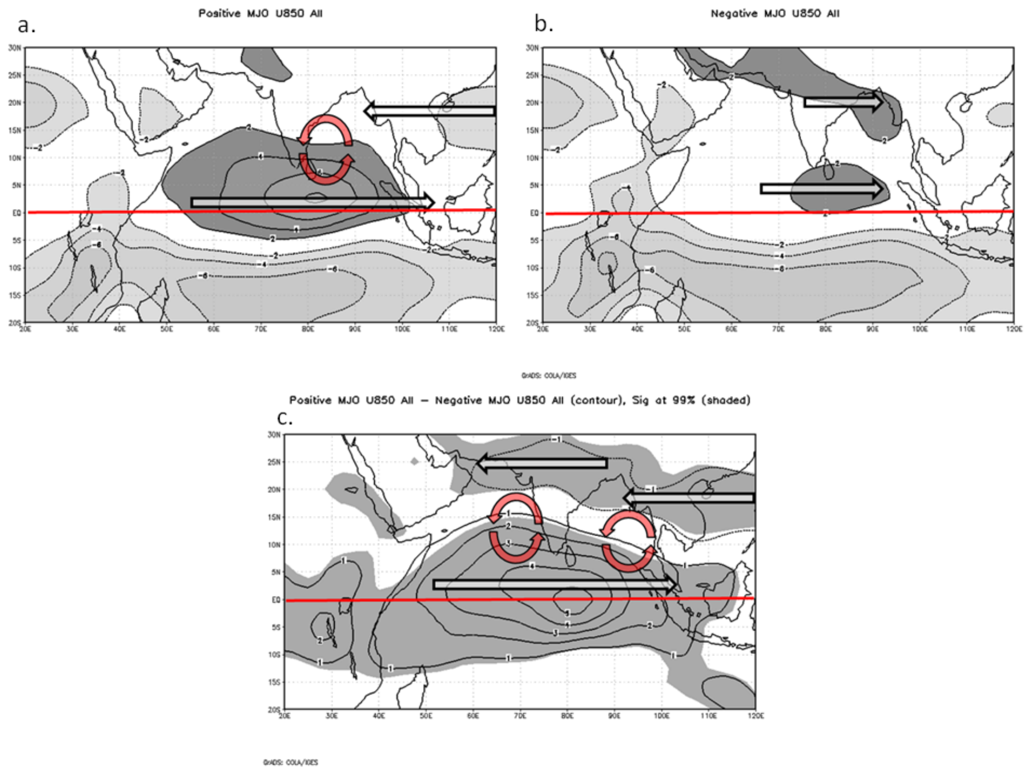

Figure 18. Composite U850 winds (m s^{-1}) when the MJO is: (a) positive, (b) negative, and (c) positive -negative. Shaded areas define 99% statistical significance.

Statistically significantly more convective precipitation occurs in the BoB with a maximum off the Sri Lankan east coast when the MJO is positive (Figure 19b). When the MJO is negative, enhanced convective precipitation occurs over east Africa (Figure 19c). These differences are consistent with the statistical relationship between positive MJO (negative MJO) and increased (decreased) TC activity in the NIO because more than twice as many TCs occur in the BoB compared to the AS (Tables 6 and 7).

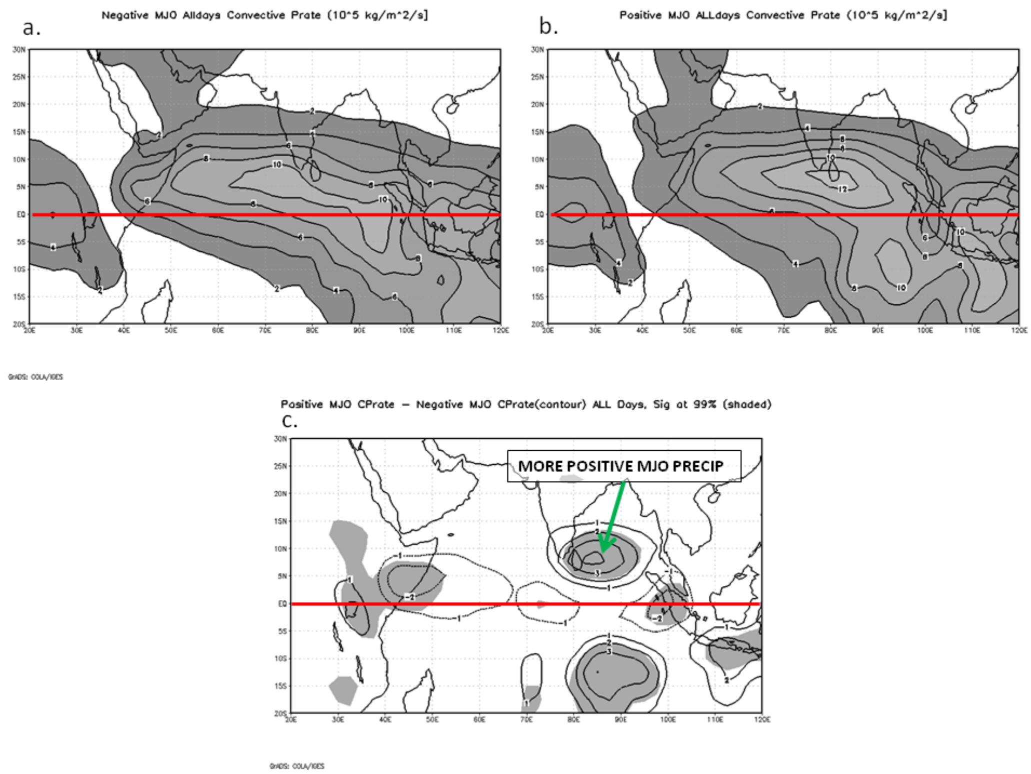

Figure 19. Composite convective precipitation (10^{-5} kg m^{-2} s^{-1}) when the MJO is: (a) positive, (b) negative, and (c) positive MJO - negative MJO. Shaded areas define 99% statistical significance.

4. ENSO AND IOD Composites

A negative IOD occurring during La Niña periods is the ENSO/IOD combination with the most statistically significant relationship to increased NIO TC activity (Table 5). A positive IOD that occurs during El Niño periods is the ENSO/IOD/MJO combination with the most statistically significant relationship to decreased NIO TC activity (Table 5). Composites of La Niña/negative IOD and El Niño/negative IOD days were prepared using only the months of the two NIO TC seasons.

Tropical easterlies from the west Pacific extend into the northern BoB and interact with the strong equatorial westerlies to influence cyclonic flow in the eastern NIO when the IOD is negative during periods of La Niña (Figure 20b). Westerly U850 wind anomalies are weaker and widespread over the NIO when

the IOD is positive during El Niño periods (Figure 20a). Differences between these composites define significantly more anticyclonic (cyclonic) background flow over the NIO when the IOD is positive during periods of El Niño (negative during periods of La Niña) (Figure 20c). These differences are consistent with the statistical relationships between negative IOD during La Niña periods (positive IOD during El Niño periods) and increased (decreased) TC activity in the NIO (Table 5).

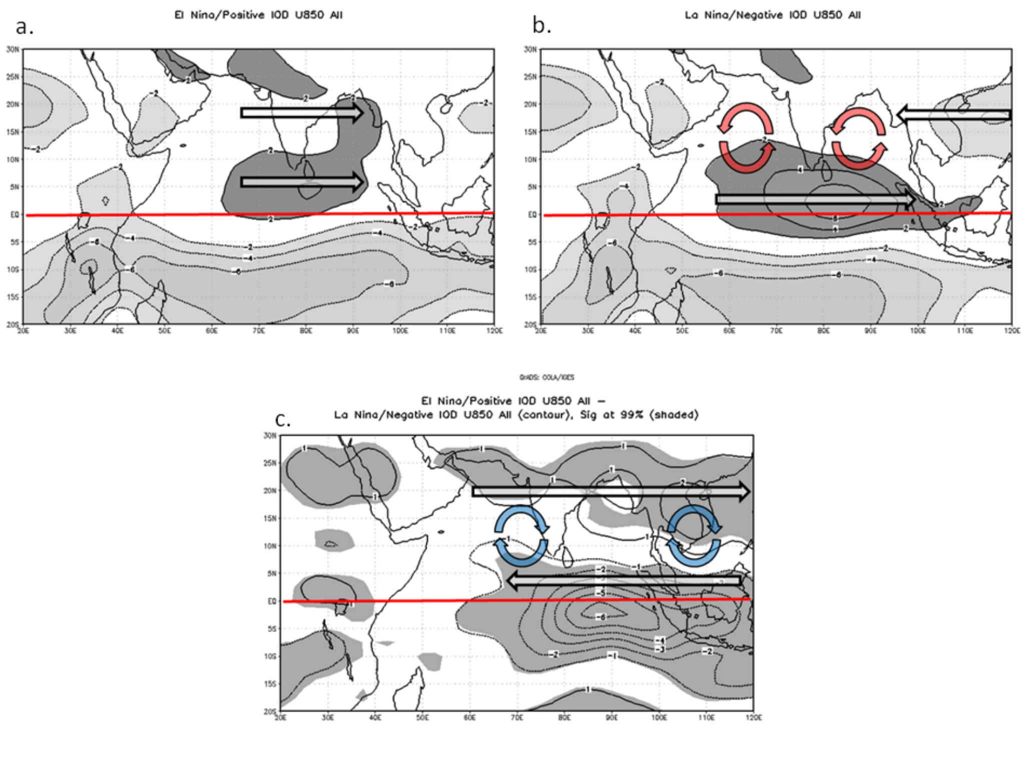

Figure 20. Composite U850 winds (m s^{-1}) when the ENSO and IOD are: (a) El Niño and positive IOD, (b) La Niña and negative IOD, and (c) El Niño/positive IOD - La Niña/negative IOD. Shaded areas define 99% statistical significance.

Enhanced convective precipitation occurs over most of the BoB with a maximum off the Sri Lankan east coast when the IOD is negative during periods of La Niña as to a positive IOD during periods of El Niño (Figure 21b). Differences between these composites are consistent with the statistical

relationships between positive (negative) MJO and increased (decreased) TC activity in the NIO because more than twice as many TCs are found in the BoB as compared to the AS (Tables 6 and 7).

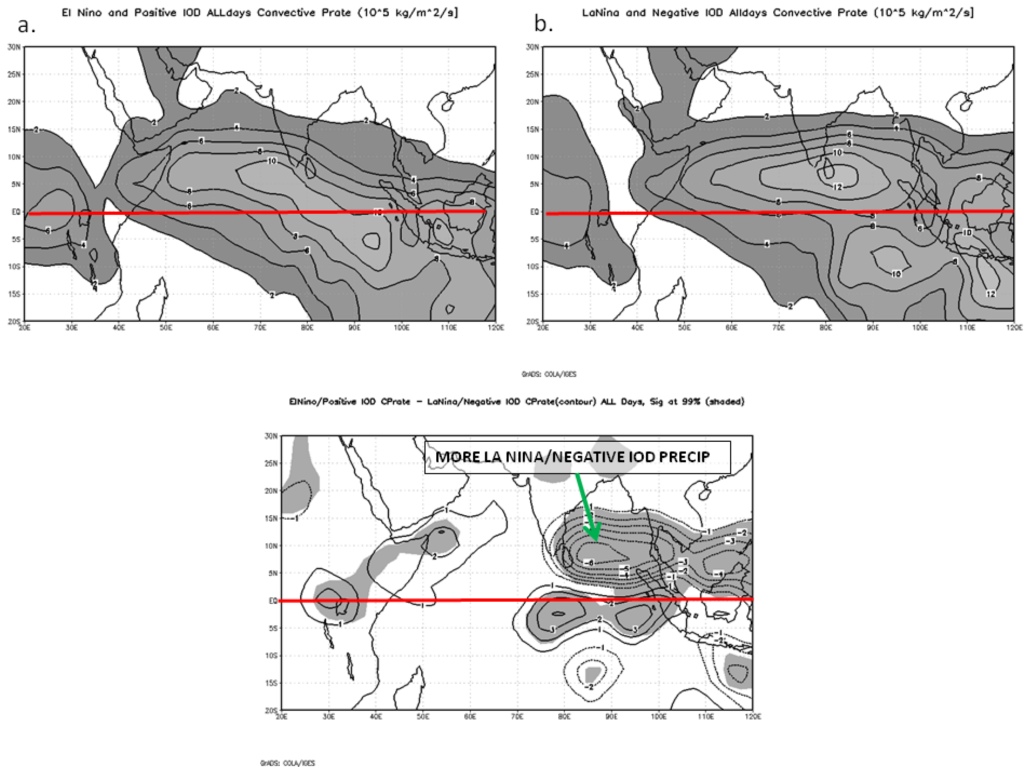

Figure 21. Composite convective precipitation (10^{-5} kg m^{-2} s^{-1}) when the ENSO and IOD are: (a) El Niño and positive IOD, (b) La Niña and negative IOD, and (c) El Niño and positive IOD - La Niña and negative. Shaded areas define 99% statistical significance.

5. ENSO AND MJO Composites

The positive MJO occurring during periods of El Niño is the ENSO/IOD/MJO combination with the most statistically significant relationship to increased NIO TC activity (Table 24). The negative MJO occurring during periods of La Niña is the ENSO/IOD/MJO combination with the most statistically significant relationship to decreased NIO TC activity (Table 25).

Equatorial westerlies are strong when the MJO is positive (Figure 22a) during periods of El Niño. This pattern increases the background cyclonic flow over the BoB and AS. When the MJO is negative (Figure 22b) during La Niña,

weak wind anomalies are found throughout the NIO as the two circulations have opposing effects. Differences between these composites indicate statistically significantly stronger westerlies throughout most of the NIO and more cyclonic (anticyclonic) flow in the BoB when the MJO is positive during periods of El Niño (negative during periods of La Niña) (Figure 22c). These zonal wind differences are consistent with the statistical relationships between negative IOD during La Niña periods (positive IOD during El Niño periods) and increased (decreased) TC activity in the NIO (Table 5).

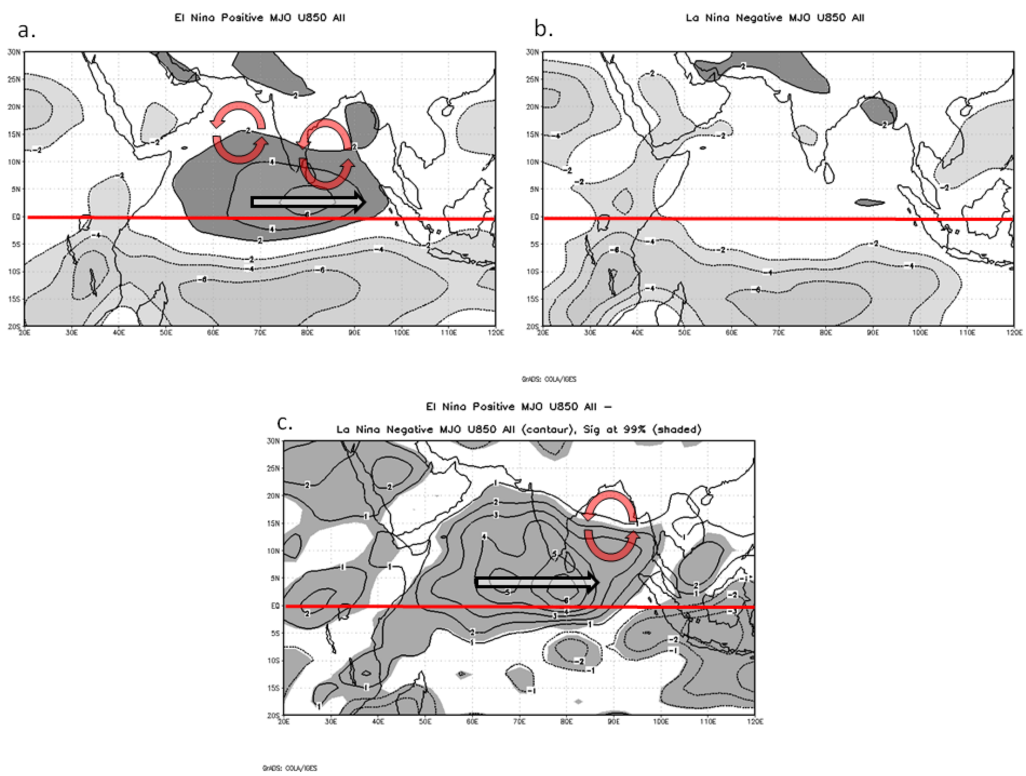

Figure 22. Composite U850 winds (m s^{-1}) when the ENSO and MJO are: (a) El Niño and positive MJO, (b) La Niña and negative MJO, and (c) El Niño/positive MJO - La Niña/negative. Shaded areas define 99% statistical significance.

6. ENSO, IOD, and MJO Composites

The positive MJO occurring during a negative IOD in periods of El Niño is the ENSO/IOD/MJO combination with the most statistically significant relationship to increased NIO TC activity (Table 24). A negative MJO that occurs

during a negative IOD in periods of El Niño is the ENSO/IOD/MJO combination with the most statistically significant relationship to decreased NIO TC activity (Table 25). Composites of El Niño/negative IOD/positive MJO and El Niño/negative IOD/negative MJO days was performed using only the months of the two NIO TC seasons.

The tropical easterlies from the west Pacific extend into the NIO and are very prominent when the IOD is negative during periods of El Niño (Figure 23b). When the MJO is positive (Figure 23a) with these ENSO and IOD phases, the easterlies from the west Pacific and equatorial westerlies are much stronger than when the MJO is negative (Figure 23b). Differences between these two composites indicate statistically significantly more background low-level confluence (diffluence) and cyclonic (anticyclonic) flow in the southern BoB when the MJO is positive (negative) during periods of El Niño and negative IOD (Figure 23c). These findings support the statistical relationship previously found between positive (negative) MJO when the IOD is negative during periods of El Niño and increased (decreased) TC activity in the NIO (Table 5).

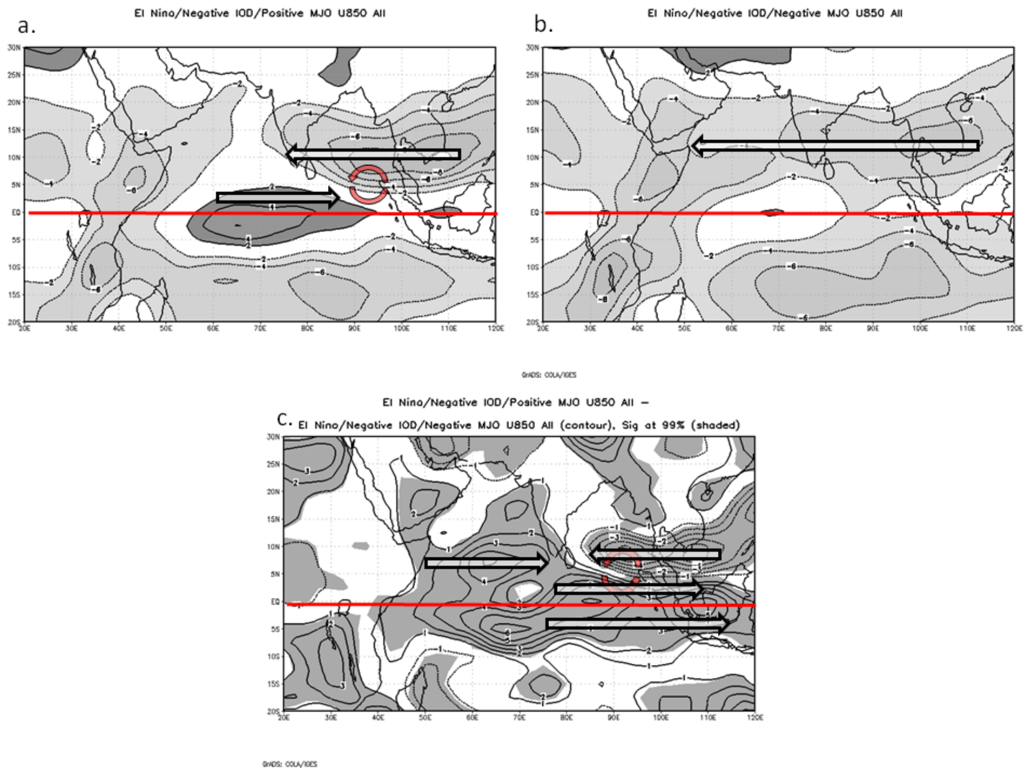

Figure 23. Composite U850 winds (m s^{-1}) with a negative IOD during periods of El Niño and the MJO is: (a) positive, (b) negative, and (c) El Niño/negative IOD/positive MJO - El Niño/negative IOD/negative MJO. Shaded areas define 99% statistical significance.

Convective precipitation in the NIO when the IOD is negative during periods of El Niño and the MJO is positive and negative is significantly larger in the southern BoB with a maximum off the Sri Lankan east coast when the MJO is positive (Figure 24a) than when the MJO is negative (Figure 24c). These findings support the statistical relationship previously found between positive (negative) MJO and increased (decreased) TC activity in the NIO when the IOD is negative during periods of El Niño (Tables 6 and 7).

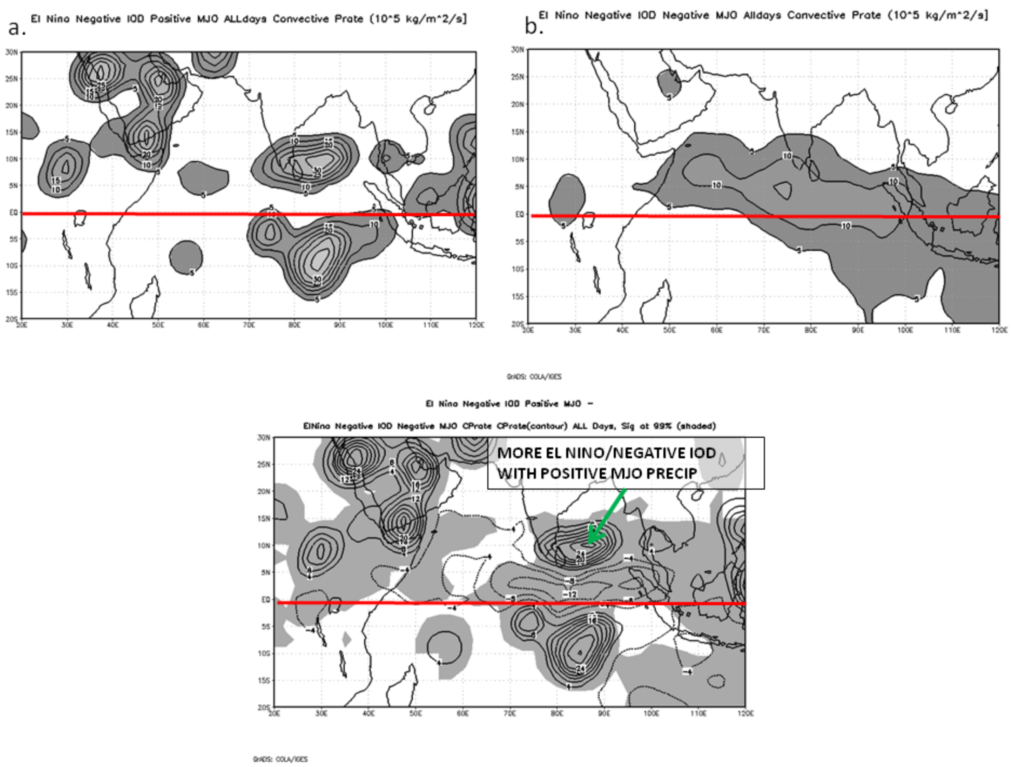

Figure 24. Composite convective precipitation (10^{-5} kg m^{-2} s^{-1}) with a negative IOD during periods of El Niño and the MJO is: (a) positive, (b) negative, and (c) El Niño/negative IOD/positive MJO - El Niño/negative IOD/negative MJO. Shaded areas define 99% statistical significance.

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IV. SUMMARY, CONCLUSIONS, AND RECOMMENDATIONS

A. SUMMARY AND CONCLUSIONS

As hypothesized, the climatic variations of ENSO, IO, and MJO have significant relationships with TC activity in the NIO. In terms of ENSO, La Niña was found to be associated with increased TC activity in the NIO, neutral ENSO with decreased activity, and no significant relationship with El Niño (Figure 25). In terms of IOD, negative IOD was found to be associated with increased TC activity in the NIO, positive IOD with decreased activity, and no significant relationship with neutral IOD (Figure 25). The convective and non-convective phases of the MJO increased the statistical significance to increased and decreased TC activity in the NIO, respectively, for all phases of ENSO and IOD. The weak MJO damped the impact of IOD and ENSO on TC enhancement and suppression for all ENSO and IOD phases except El Niño and neutral IOD, which is where the weak MJO increased statistical significance to decreased TC activity (Figure 1). The most significant relationship between TC activity in the NIO and any combination of ENSO, IOD, and MJO circulations was El Niño with positive IOD for increased TC activity, and La Niña with a negative IOD for decreased activity (Figure 25).

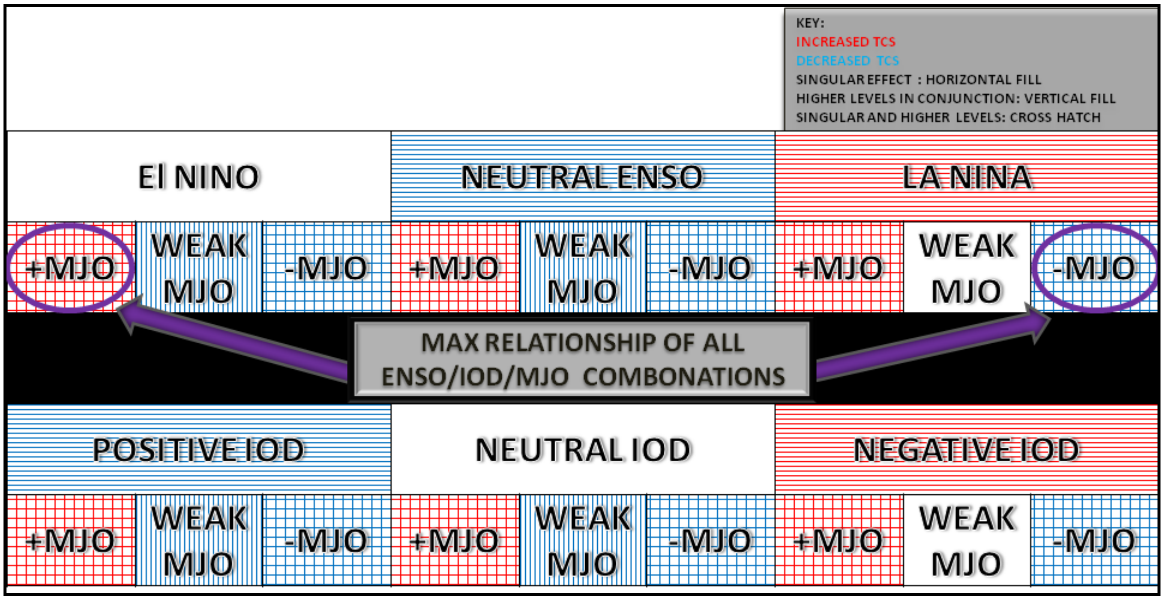

Figure 25. ENSO and MJO relationship flowchart. Horizontal line fill corresponds to singular effect on NIO TC activity. Vertical line fill corresponds to accumulated effects of all larger-scale circulations on NIO TC activity. Crosshatch fill corresponds to singular and accumulated effects of larger scale circulations on NIO TC activity. Red fill corresponds to increased NIO TC activity and blue fill corresponds to decreased NIO TC activity. Maximum statistical significance to TC activity in the NIO of all ENSO/IOD/MJO combinations is positive MJO/El Niño for increased TCs and negative MJO/La Niña to decreased TCs.

El Niño periods in conjunction with positive IOD have the most significant relationship to decreased activity, while La Niña with negative IOD have the most significant relationship to decreased activity (Figure 26). When La Niña (neutral ENSO) and positive IOD (negative IOD) occur together, the circulations tend to be opposing, which results in no statistical significance (Figure 26). When ENSO, IOD, and MJO occur concurrently, the most significant positive (negative) relationship with NIO TC activity occur during El Niño and negative IOD when the MJO is positive (negative) associated with increased (decreased) TC activity (Figure 26). Therefore, it is concluded that the influence of the MJO dominates over the impact of larger-scale, slowly-varying ENSO and IOD circulations.

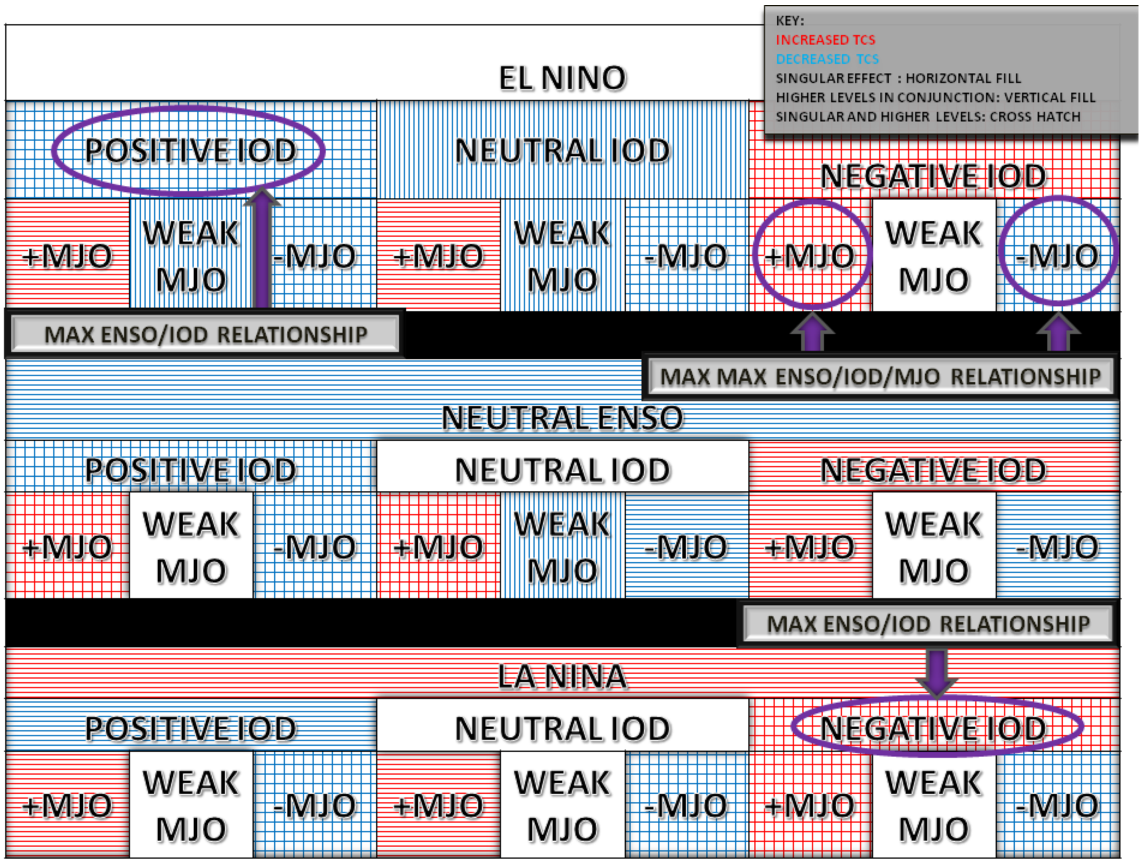

Figure 26. ENSO and MJO relationship flowchart. Horizontal line fill corresponds to singular effect on NIO TC activity. Vertical line fill corresponds to accumulated effects of all larger-scale circulations on NIO TC activity. Crosshatch fill corresponds to singular and accumulated effects of larger scale circulations on NIO TC activity. Red fill corresponds to increased NIO TC activity and blue fill corresponds to decreased NIO TC activity. Maximum statistical significance to TC activity in the NIO of all ENSO/IOD combinations is negative IOD with La Niña for increased TCs and positive IOD with El Niño for decreased TCs. Maximum statistical significance to TC activity in the NIO of all three-way ENSO/IOD/MJO combinations is negative IOD/El Niño with positive MJO for increased TCs and negative IOD/El Niño with negative MJO for decreased TCs.

B. RECOMMENDATIONS FOR FUTURE RESEARCH

This research may serve as the groundwork for future long-term forecast products regarding TCs in the NIO. It would be beneficial to perform a similar examination using established ENSO, IOD, and MJO prediction products.

Another future study could also be a similar analysis to this research only comparing TC activity in the NIO and climatic oscillations with a three-month lag.

Since significantly more current military operations are in the Arabian Sea rather than the Bay of Bengal, future work could be to establish a better understanding of what impacts the TC activity in the northwest IO.

In addition of the climatic oscillations variations examined in this research, other variations such as the Arctic Oscillation could also enhance results by giving higher statistical significance values if relationships were found.

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